Nearshore Hypoxia as a New Lake Erie Metric

FINAL REPORT

LAKE ERIE PROTECTION FUND PROJECT SG 334-07

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Executive Summary

The purposes of this project were to (1) measure concentrations of dissolved oxygen (DO) repeatedly in 2007 near the southern shore of the central basin of Lake Erie in order to detect occurrences of hypoxia or anoxia near the lake bottom where depths are shallower than 20 meters; (2) compare DO concentration profiles among the years 2005, 2006, and 2007; and (3) assess the potential benefits of adding a "central basin nearshore hypoxia" metric to the Lake Erie Quality Index. In this report, hypoxia is defined as a dissolved oxygen concentration of at least 1.0 mg/L and less than 2.0 mg/L, and anoxia is defined as a concentration below 1.0 mg/L. Data collected by staff of the Franz Theodore Stone Laboratory in 2005 at two stations in the western end of the basin revealed persistent anoxia at depths as shallow as 15 m. Data from two transects perpendicular to the southern shore near Lorain, Ohio, in 2006 and 2007 through an Ohio Sea Grant (2006) and this grant (2007) showed a large area of persistent anoxia at depths as shallow as 14 m in 2006, and localized areas of anoxia both years at depths as shallow as 11 m. Thus, it appears that, if the study areas are representative of other regions of the central basin shallower than 20 m, anoxia is sufficiently widespread and persistent to account for the degraded benthic invertebrate communities that have characterized shallow regions of the basin for decades.

Data on dissolved oxygen concentrations near the lake bottom have been amassed over a period of several decades by a variety of US and Canadian agencies. However, no concerted effort has been made to look for spatial patterns in DO concentrations in waters less than 20 m deep or to discover trends in the extent, duration and severity of oxygen depletion in those shallow waters. We suggest that a "central basin hypoxia" metric should be considered by the Ohio Lake Erie Commission for addition to the Lake Erie Quality Index, perhaps as a component of the Water Chemistry Metric of the Ambient Water Quality Indicator. A hypoxia metric could serve in the central basin in place of the Hexagenia *mayfly component of the Key Indicator Species metric of the Biological Indicator as long as* Hexagenia *continues to be absent from the basin because the distribution of* Hexagenia *appears to be determined by minimum DO concentrations in summer.*

A hypoxia metric would provide the following advantages: (1) direct measurement of variation from year to year in the timing, duration, extent, and severity of hypoxia events in shallow (<20 m) coastal waters; (2) direct evidence to support explanations of degraded zoobenthic communities in shallow regions of the central basin; (3) a gauge for monitoring year-to-year changes in areal extent and duration of hypoxia and anoxia in shallow regions of the basin, and thus trends toward improvement or further degradation over time; (4) data to assist calibration and validation of hypoxia models for the central basin being developed NOAA's Great Lakes Environmental Laboratory and others. Potential disadvantages of a hypoxia metric would include (1) another set of data to be collected while performing other functions aboard research vessels, (2) another set of data to be computerized and maintained by agency staff, (3) desirability of coordinated (simultaneous) data collection along the north and south shores and western end of the basin, (4) need to apply identical sampling methods across agencies. Specific criteria upon which a hypoxia metric would be scored annually would need to be developed by collaborating agencies.

Introduction

Data dating to the late 1990s indicate an increase in the size and seasonal duration of the "dead zone", or the area of anoxia (no dissolved oxygen) and hypoxia (near-absence of dissolved oxygen) in the hypolimnion of the central basin of Lake Erie (www.epa.gov/glnpo/glindicators/water/oxygenb.html). Change in the "dead zone" has been accompanied by changes in central basin chemistry, including an increase in phosphorus concentrations (www.epa.gov/glnpo/glindicators/water/phosphorusa.html). These indications of a return to lower water quality in the basin have resulted in renewed efforts by scientists and managers to understand the physical, chemical, and biological dynamics of the hypolimnion.

The summer hypolimnia of temperate lakes throughout the world are known to be dynamic rather than stationary (Kalff 2002). Weather events, particularly strong and prolonged windstorms, set the hypolimnion into motion with the result that part of the hypolimnion, which forms in the coolest and deepest regions of a lake basin, may intrude temporarily into shallow regions. Such events appear to be relatively frequent in many large lakes. For example, Effler *et al.* (2004) documented an 11-hour upwelling event in Onondaga Lake, New York, in September 2002 that brought hypolimnion water to the lake surface and resulted in dissolved oxygen (DO) concentrations below 1 mg/L in surface waters at the windward end of the lake, and they estimated that at least 14 such events occurred within the interval 1990-2002. Similarly, it is known that the hypolimnion of Lake Erie's central basin is dynamic from the time it forms in June or July until it dissipates in September or October (Bartish 1987, Royer *et al*. 1987). The dynamics are three-dimensional. Hypolimnion thickness varies, both by seasonal erosion of the metalimnion and by internal seiches and upwelling events that result from forcing events such as windstorms and barometric pressure gradients (Bedford 1992).

Lateral movements or expansions of the hypolimnion into areas of Lake Erie usually occupied by the metalimnion or epilimnion (e.g., Bartish 1987) have been reported infrequently and few if any data are routinely collected that demonstrate these movements. Buoys deployed since 2003 or earlier by Ohio Sea Grant, University of Windsor, and NOAA's Great Lakes Environmental Research Laboratory (GLERL) at several points in the central basin provide data on time of hypolimnion establishment, progressive change in thickness, temperature profile, and vertical oscillations of temperature at those specific points in the lake. For example, GLERL Buoy No. 5 (41.6745° N, 82.6258° W) at the juncture of the western and central basins collects temperature and turbidity data at 1 m and 8 m above the lake bottom (11 m) (www.glerl.noaa.gov/res/Programs/erie/pgs/moorings.html). However, the data collected at that and similar sites do not provide direct information about dynamics of the hypolimnion in the coastal zone.

The impetus for this study was largely driven by the biology of the central basin. Our field studies in the central basin over the past 30 years (Krieger 1984, Krieger and Ross 1993) have led to the following hypotheses. Hypothesis 1: That the distribution and abundance of major zoobenthic species (round gobies and other benthic fishes, zebra and quagga mussels, mayflies, midges, and others) near the margins of the central basin are determined by transitory (hours-long to days-long) shifts in the position of oxygen-depleted hypolimnion waters. Hypothesis 2: That high-resolution, frequent observation of lateral hypolimnion dynamics coupled with observation of differences in zoobenthic community structure (composition and age distribution) and abundance can explain the general absence of hypoxia-sensitive zoobenthic species from vast areas of the central basin that have not heretofore been shown to experience hypoxia or anoxia. In this report we define hypoxia as a dissolved oxygen (DO) concentration from 1.0 mg/L to less than 2.0 mg/L and anoxia as a DO concentration below 1.0 mg/L.

Evidence in support of Hypothesis 1 includes the following: (1) Vast areas of central basin sediments have the proper consistency and grain size composition to support *Hexagenia* mayfly nymphs, as they do in most of the western basin, but are devoid of the nymphs. Those same sediments do support substantial populations of invertebrates tolerant of anoxia, such as oligochaetes worms and chironomid midges (Krieger 1984, 2005, 2006; Krieger and Ross 1993. (2) In the spring of 2004, a young cohort of *Hexageni*a nymphs that hatched that spring or the previous fall was present in sediments near the western edge of the central basin, but the expected older cohort, which would have emerged in the summer of 2004, was absent, indicating that the life cycle was interrupted in the summer of 2003, probably as a result of anoxia (Krieger 2005). If that situation was typical, it appears that each year *Hexagenia* eggs are dispersed into the central basin and successfully hatch [the eggs are tolerant of anoxia (Britt 1955)] but the nymphs succumb to anoxia the following summer. (3) The emergence of small numbers of adult *Hexagenia* from the central basin every summer, noted by their appearance on shoreline structures, in regions where nymphs apparently are absent in nearshore sediments (Krieger 2004), suggests the existence of very-nearshore refugia, perhaps within marinas and harbors of the central basin. Sediment samples from 62 stations in those areas in May-June 2005 (Krieger 2006) yielded mayfly nymphs only at two stations. This indicates that *Hexagenia* nymphs are indeed very sparsely populated in as yet mostly unknown parts of the central basin. (4) A historical basis for Hypothesis 1 exists in data gathered by our laboratory (NCWQR) in 1978 and 1979 in which DO at 1 m above the bottom at some central basin stations, particularly in the Sandusky subbasin, varied from >5 mg/L to <1 mg/L on consecutive days (Richards 1981). (5) Bartish (1987) reported an intrusion of central basin hypolimnion water far into Pigeon Bay of the western basin. He suggested that similar intrusions may occur one to two times per year.

The role of DO in controlling the structure (species composition and abundance), distribution and biomass of the benthic and benthic-pelagic food webs is unknown because high-resolution spatial and temporal data on DO concentrations near the coastal margins of the central basin are lacking both presently and historically. Even though the short-term lateral dynamics of the hypolimnion have largely been overlooked, they likely exert a strong impact on the ecology of the nearshore and westernmost regions of the basin. Excursions of hypoxic water into those areas may render large expanses of the central basin inhospitable to a "healthy" biological community that is needed to sustain a viable fishery. Documentation of hypolimnion dynamics at the local scale should provide direct evidence of the primary cause of continued degradation of the bottom community of shallower waters of the central basin at a time when the integrity of the community of the western basin has to a large extent been restored (Schloesser *et al*. 2000).

The objectives of this project were to (1) characterize the three-dimensional dynamics of the hypolimnion of the central basin, with a focus on short-term movements of the lateral boundary of the hypolimnion into shallow coastal waters; (2) compare DO data from the summers of 2005, 2006 and 2007 with meteorological conditions reported from a nearby NOAA weather buoy in order to discover predictive relationships between hypolimnion intrusions and preceding weather conditions; and (3) assess the potential for nearshore hypoxia to serve as a new metric for the central basin in the Ohio's Lake Erie Quality Index (OLEC 2004).

Study Area

Stations were designated along transects AP and BR oriented approximately perpendicularly to the southern shore of the central basin between Lorain and Rocky River, Ohio (Figure 1). The interval between stations was 0.012°N closer to shore and 0.025°N farther from shore (Table 1), and station depths ranged from 8.5 m to 18.5 m on transect AP and 7.0 m to 16.5 m on transect BR (Table 1). The most shoreward and shallowest station on each transect was 1.0 km (BR) or 1.2 km (AP) offshore, and stations were generally progressively deeper with increasing distance from shore. The total distance between the most shoreward and most lakeward stations was 11.3 km (AP) or 12.5 km (BR), and the distance between transects was approximately 14 km (Figure 1). The basin morphometry in the vicinity of the transects is characterized by a rapid increase in depth within 2 km of shore to about 14 m at transect AP and to about 10 m at transect BR, followed further offshore by a very gradual increase in depth, especially along transect BR (Figure 1).

In 2005, staff of the F. T. Stone Laboratory (The Ohio State University) deployed a YSI data sonde attached to a buoy at each of two stations, SL15E at approximately 15 m depth and SL20 at approximately 20 m depth (Figure 1, Table 1). These buoys were near the study transects that we observed in 2006 and 2007. Though the DO data collected in 2005 predate the present study, they have not been presented elsewhere and are included in this report to enhance interpretation of the physical processes that operate during stratification every summer in the central basin. In addition, we downloaded (www.ndbc.noaa.gov/station_history.php?station=45005) wind and wave data from a NOAA weather buoy (Station 45005) near the study transects (Figure 1, Table 1) to help explain our water temperature and DO observations.

Methods

Each of the two data sondes deployed in 2005 were connected to a vertical string of thermistors and a DO electrode situated 0.2 m off the bottom. The DO electrodes were calibrated immediately prior to deploying them on 10 July 2005, and the sondes recorded data continuously at hourly intervals until they were retrieved on 3 October.

The temperature and DO measurements conducted through this LEPF project in 2007 provided a second year of measurements similar to those made in 2006 through an Ohio Sea Grant (www.ohioseagrant.osu.edu/research/aquaticecology/?ID=R/ER-077-PD). The methodology was identical in both studies. We visited stations along both transects during two sampling intervals each summer: 24-27 July 2006 (spanning 4 days), 16-18 and 22 August 2006 (spanning 7 days plus 6 September), 16-18 July 2007 (3 days), and 6 and 8-10 August 2007 (5 days plus 22 August). We were able to visit one or more stations a second time on some days, usually about three hours after the initial visit, to obtain a second set of readings. Measurements were conducted aboard the *R/V Bowfin*, which could traverse rapidly from station to station. The number of stations visited on a given day and the number of days included in each sampling interval were determined by weather conditions that often changed rapidly.

On each visit a vertical profile of temperature and dissolved oxygen (mg/L and percent saturation) was recorded with a YSI 58 DO meter calibrated daily in saturated air. On infrequent occasions, two other YSI

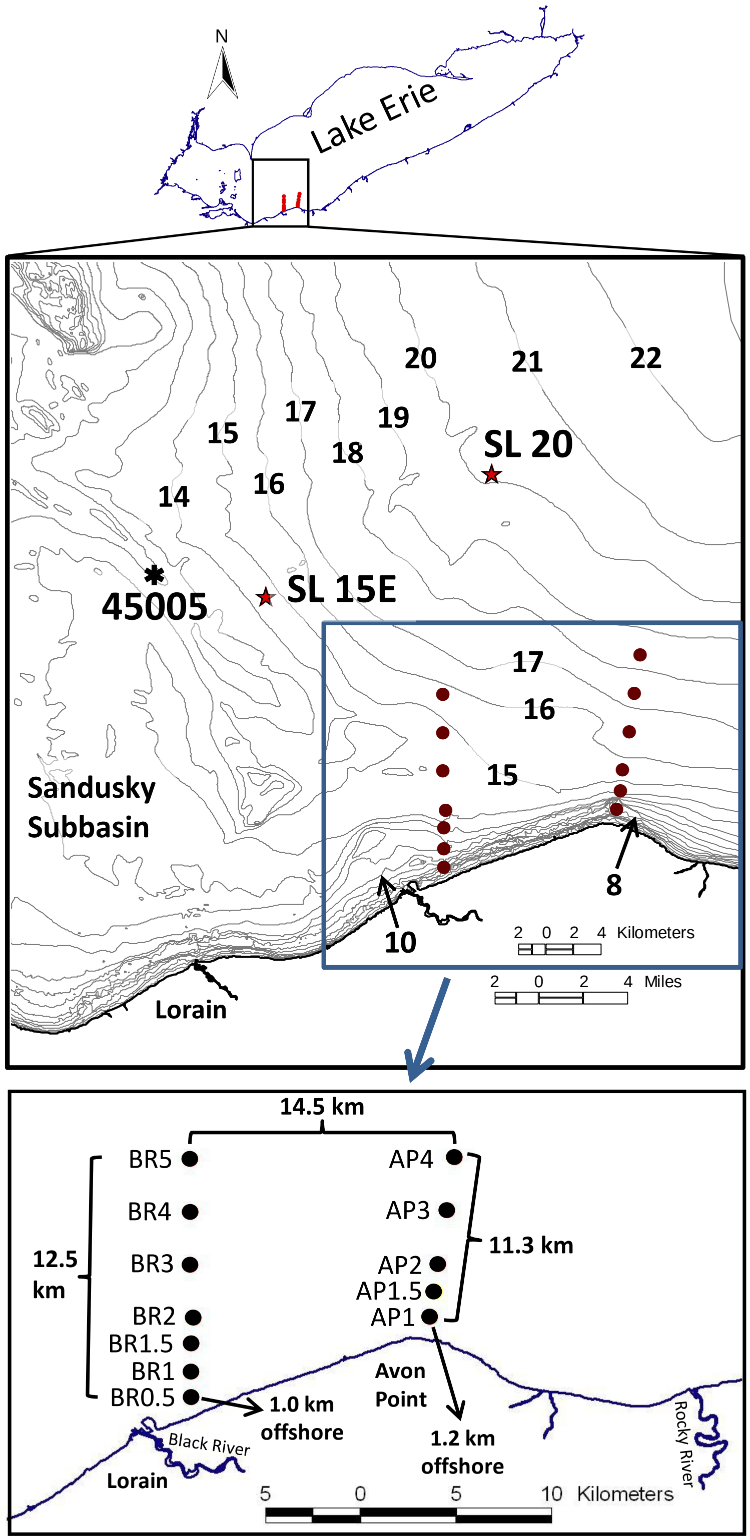

Figure 1. Study area showing location of transects in the central basin of Lake Erie (top); bathymetry (meters) in the region around the transects and in the eastern part of the Sandusky subbasin, the location of two data sondes (SL15E and SL20) deployed in 2005, and NOAA buoy 45005 (middle); and locations of stations and distance of each transect from shore, from the other transect, and along each transect (bottom).

Table 1. Coordinates of NOAA and Stone Laboratory buoys and each transect station, and minimum and maximum depths encountered while sampling in 2007.

Station	°N	°W	Min., Max. Depth, m
NOAA Buoy	41.677	82.398	–
SL15E	41.664	82.303	–
SL20	41.743	82.107	–
AP1	41.525	82.000	8.5, 8.9
AP1.5	41.537	81.997	14.5, 14.7
AP2	41.550	81.995	16.0, 16.3
AP3	41.575	81.989	16.8, 17.0
AP4	41.600	81.984	17.4, 17.6
AP5	41.625	81.979	18.5, 18.5*
BR0.5	41.488	82.150	7.0, 7.5
BR1	41.500	82.150	11.5, 11.7
BR1.5	41.513	82.150	13.1, 13.4
BR2	41.525	82.148	14.5, 14.6
BR3	41.550	82.150	15.7, 15.9
BR4	41.575	82.150	15.5, 15.5
BR5	41.600	82.150	16.4, 16.7

*Visited only on 16 July 2007

meters were used. Laboratory comparison of temperature readings and calibration of a range of DO readings for each meter against the other meters and a Winkler titration showed that all meters provided similar readings within a few tenths of a unit. Response of the thermistor to temperature change was rapid; however, response of the DO electrode was often slow. Care was taken at each depth to permit the DO electrode to approach equilibrium before recording a reading; the electrode response often required three or four minutes when very low DO concentrations were suddenly encountered in the hypolimnion. The DO electrode was weighted in order to eliminate error in recording depths that would have resulted from a nonvertical angle of the cable.

Tables and most graphs were produced using Excel 97-2003 or Excel 2007. Wind and wave vector plots were generated with SigmaPlot 11 (Systat Software, Inc. 2008) after converting wind and wave directions to radians in Excel and computing beginning and ending vector coordinates.

Results

Dissolved oxygen at 0.2 m off the lake bottom became hypoxic at Station SL15E soon after the time the data sonde was deployed on 11 July 2005 (Figure 2). There the DO concentration generally remained below 0.5 mg/L from 11 August through 16 September, when the fall turnover began. The long period of anoxia was interrupted by five episodes of two to ten days duration when the DO concentration spiked upward. Even so, from early August through mid-September the DO concentration never reached 4 mg/L and was usually <0.5 mg/L.

The deeper, 20 m station (SL20) experienced a more prolonged period of oxygen depletion than the 15 m station and revealed a generally linear rate of decline in DO concentration from the time of deployment until 19 September, when DO was no longer detectable (Figure 2). The same time periods that marked the three largest increases in DO concentration at SL15E prior to mid-September instead marked declines in concentration at SL20 that were much less dramatic than the increases at SL15E. However, fall turnover is not clearly represented in the data and was at least six days later at SL20 than at shallower SL15E.

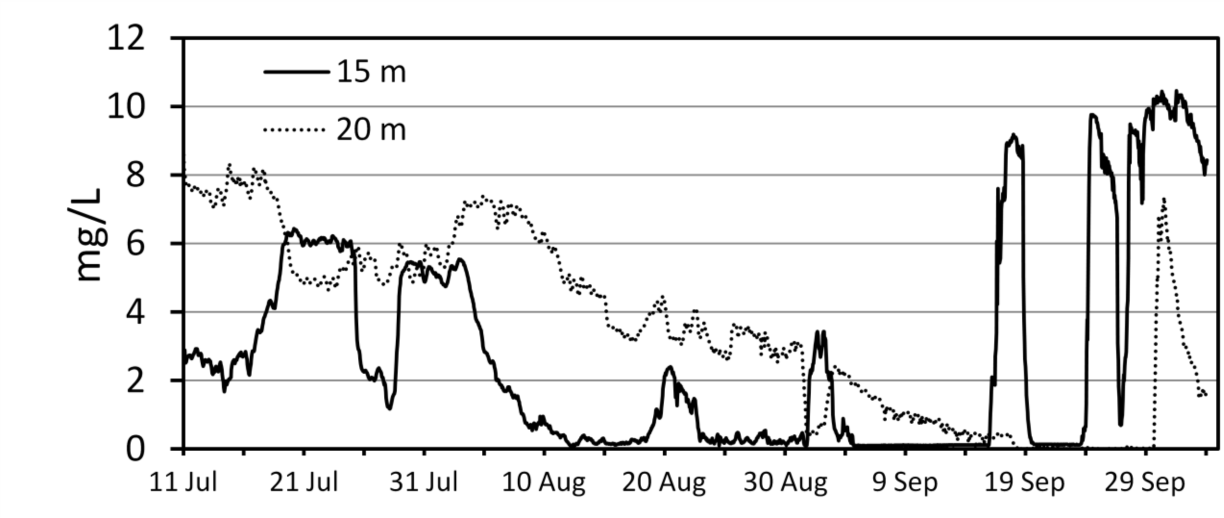

Figure 2. Changes in dissolved oxygen at stations SL15E (15 m) and SL20 (20 m) from July through early October 2005. Each date begins at the tick mark. (Data courtesy of Matt Thomas, Ohio State University, F. T. Stone Laboratory)

Complete data for transects AP and BR collected through this grant in 2007 are included in the appendix. DO concentrations within 1 m of the bottom during the two time intervals in 2006 revealed the presence of anoxia (< 1.0 mg/L) at one or more stations along both transects in late July within a few km of shore at depths as shallow as 11 m (Figure 3). Hypoxia (1.0 to < 2.0 mg/L) was more extensive than anoxia in July but was not seen as close to shore as was anoxia. Particularly noteworthy during 25-27 July 2006 along Transect BR and 16-17 July 2007 (Figure 4) on both transects were areas of anoxia in the hypolimnion that persisted shoreward of more highly oxygenated water. In August 2006, a zone of anoxia that extended beyond approximately the 15 m contour and may have represented a shoreward migration of the dead zone persisted throughout the 7-day sampling period. Renewal of oxygenated bottom water in the shallower areas close to shore occurred between 18 and 22 August, and by 6 September fall turnover had progressed to a depth of at least 16 m.

Near-bottom oxygen depletion was not as severe during observation in 2007 as in 2006 (Figure 4). Anoxia was only observed in July, and then at an intermediate bottom depth (12-14 m contours) and distance from shore along both transects, appearing as a “pocket” of anoxic water. This area of anoxia had disappeared by the third day of sampling. The August 2007 sampling period, which extended over five

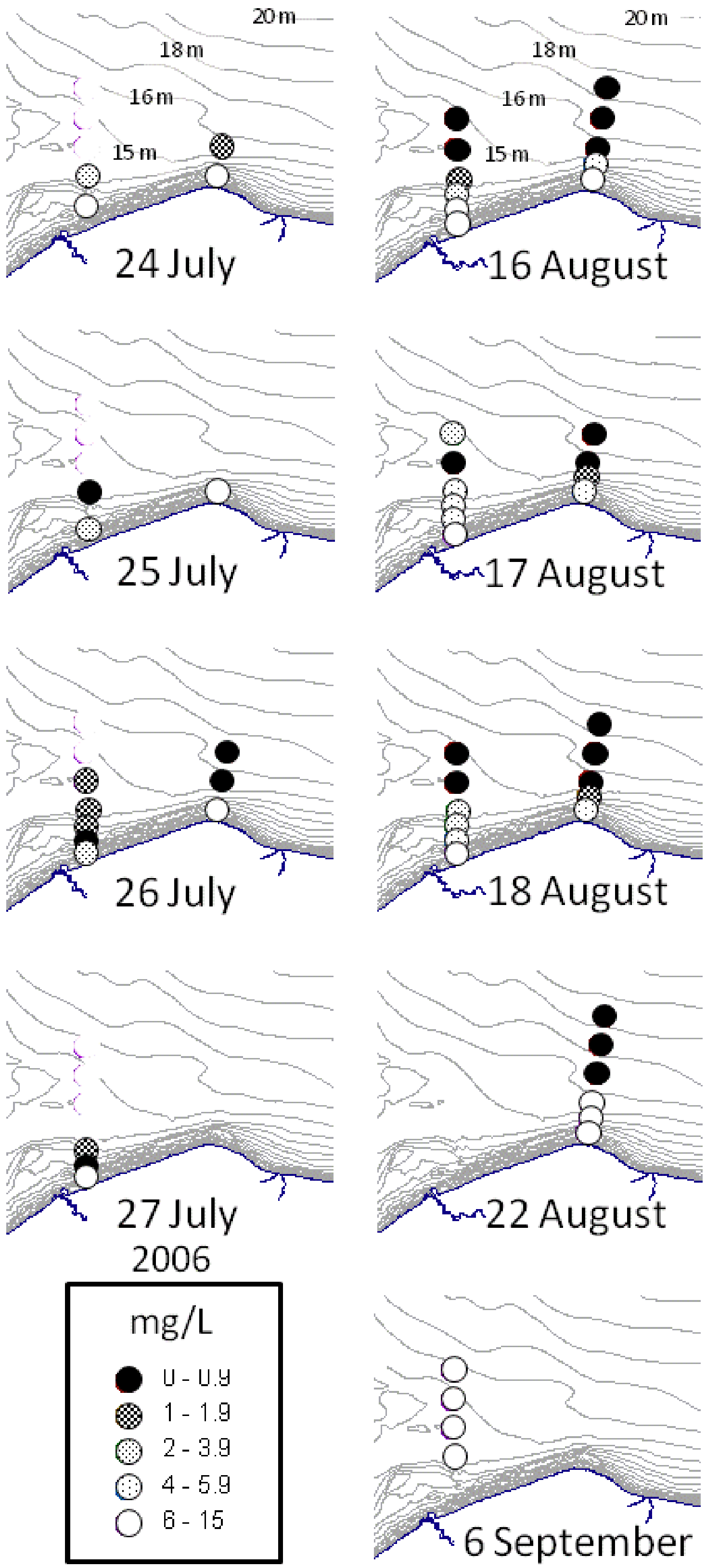

Figure 3. Dissolved oxygen concentrations within one meter of the bottom during two time intervals in July and August 2006. Stations not visited on a date are not shown.

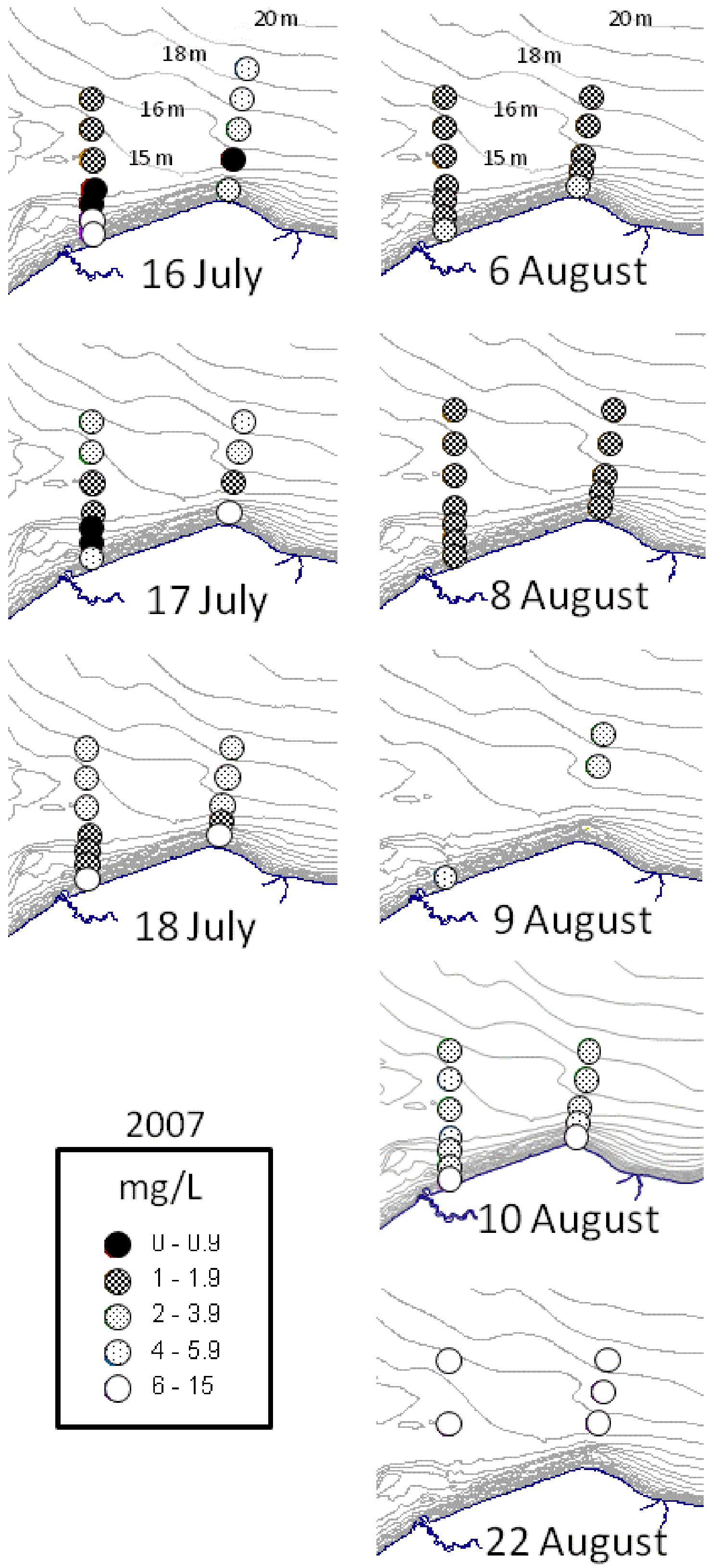

Figure 4. Dissolved oxygen concentrations within one meter of the bottom during two time intervals in July and August 2007. Stations not visited on a date are not shown.

days (plus 22 August), was characterized by near-bottom hypoxia at all stations for the first three days (6-8 August), except the station closest to shore on each transect on the first day, which also exhibited some oxygen depletion (2-4 mg/L). Partial or complete reoxygenation had occurred at all stations by the fifth day (10 August), and concentrations were ≥6.0 mg/L at all stations (15-17 m) by 22 August.

The vertical profiles of temperature and DO concentration corresponded closely with each other (Figure 5). The thickness of the epilimnion and the depth of the thermocline increased as lake depth increased, whereas the upper limit of the hypolimnion and hypolimnion temperature decreased with increasing lake depth. Within the epilimnion, with its nearly uniform temperature, DO concentration often was slightly greater several meters below the surface. Thermal stratification was reflected by vertical differences in DO concentrations, but whereas the temperature was fairly uniform throughout the hypolimnion, the DO concentration declined somewhat with increasing depth. As shown for example at Station BR0.5 on 17 July 2007, even though temperature declined only 1°C between the top and bottom of the water column and no hypolimnion was present, the DO concentration declined dramatically near the bottom (Figure 5).

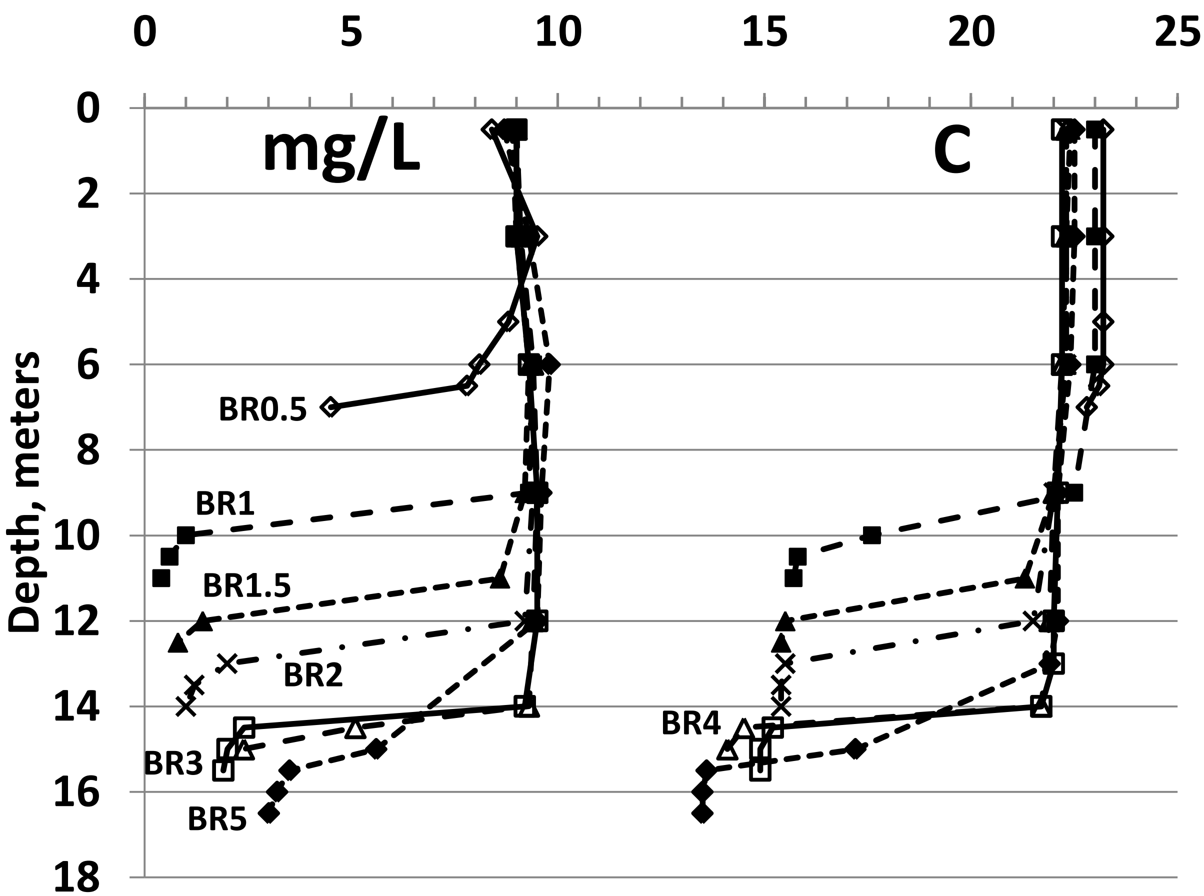

Figure 5. Vertical profiles of dissolved oxygen concentration (mg/L) and temperature (°C) at six stations along transect BR on 17 July 2007 showing a thickening epilimnion and a descending thermocline as depth and distance from shore increase. The deepest measurement at each station is within 1 m of the bottom.

The vertical profiles of temperature and DO concentration occasionally varied substantially from day to day and even within a few hours (Figure 6). For example, during the period 24-27 July 2006, the daytime surface DO concentration at Station BR1 varied by approximately 1.5 mg/L, and within 1 m of the bottom DO concentration declined approximately 7 mg/L, from near 7.5 mg/L on 24 July to 0.5 mg/L on 26 July, and within only three hours on 25 July the DO concentration dropped by 4 mg/L. Furthermore, during those four days the hypolimnion varied in thickness from approximately 1 m to 3 m (as reflected by the vertical profile of DO concentration, Figure 6).

Multiple vertical profiles can be converted to depth-time diagrams to assist in visualizing the duration and depth of anoxic water at a particular station and in comparing changes over time in the vertical profiles of temperature and DO concentration. Depth-time diagrams for Station BR1 (Figure 7) show the thickness and duration (to the end of our observation period) of near-bottom anoxia and hypoxia in July and the absence of hypoxia in August 2006, and they illustrate the correspondence of DO concentration patterns with temperature patterns from day to day.

Likewise, isopleths of temperature and DO can show differences in temperature and DO concentration along a transect at a point in time. For example, isopleths demonstrate a localized area of anoxia, and hypoxia at all depths, along Transect BR on 26 July 2006 (Figure 8). Isopleths also reveal the extensive region of anoxia in the hypolimnion of both transects on 16 August 2006 (Figure 9). Several

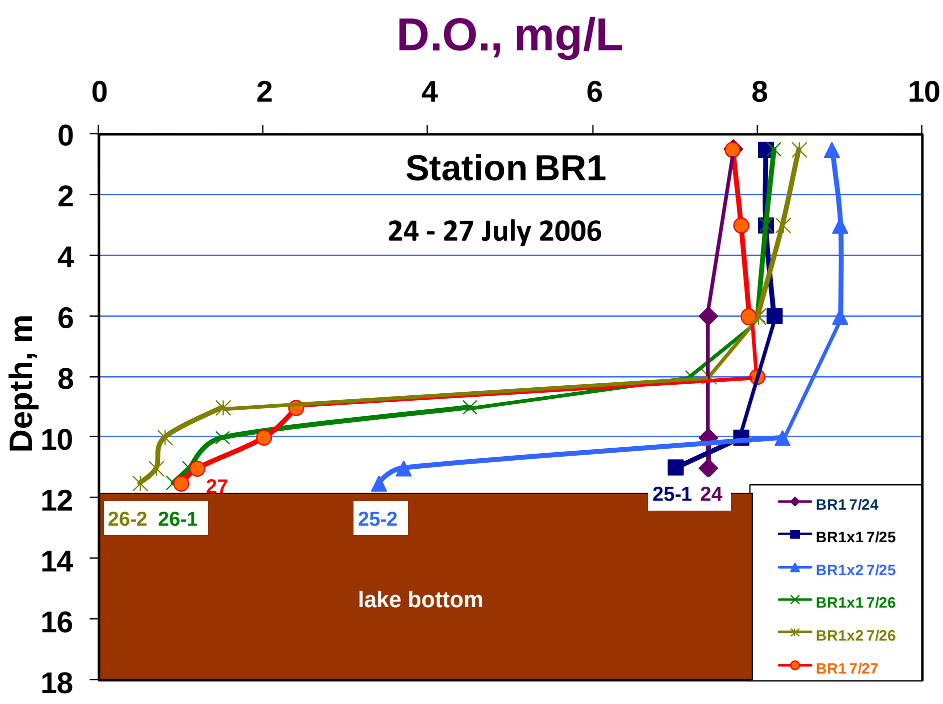

Figure 6. Example of change over time observed in the vertical dissolved oxygen profile at individual stations. Here, at Station BR1 vertical profiles were measured once on 24 July and twice on 25 July and 26 July. The first profile (25-1, 26-1) was measured in late morning; the second profile (25-2, 26-2) was measured approximately three hours later in early afternoon.

stations near shore on Transect BR that were revisited three hours later on 16 August 2006 indicated an increase in DO concentration at all depths. Changes at the deeper stations are not known because they were not revisited.

Discussion

The extensive data from two buoys in 2005 and our data from a small geographic area of Lake Erie for brief periods during the summers of 2006 and 2007 confirm that dissolved oxygen concentrations in the central basin near the margins of the hypolimnion are highly dynamic. Our data from shoreward areas <18 m deep are limited, yet it is likely that to some degree they characterize summer dynamics all along both the north and south shores of the central basin.

The buoy data for 2005 indicate that the rate of oxygen depletion in the western central basin is relatively constant through the summer until anoxia is attained (Figure 2). Depletion is punctuated by sporadic events characterized by a sudden increase (at 15 m) or decrease (at 20 m) in DO concentration. DO depletion was well underway at 15 m at the time of buoy deployment on 11 July, whereas approximately 15 km to the northeast at 20 m DO was near saturation at that time (Figure 2). Two possibly concurrent mechanisms for this could be that (1) the thinner hypolimnion of the 15 m station, by containing a smaller quantity of DO, becomes depleted more rapidly than the thicker hypolimnion at 20 m,

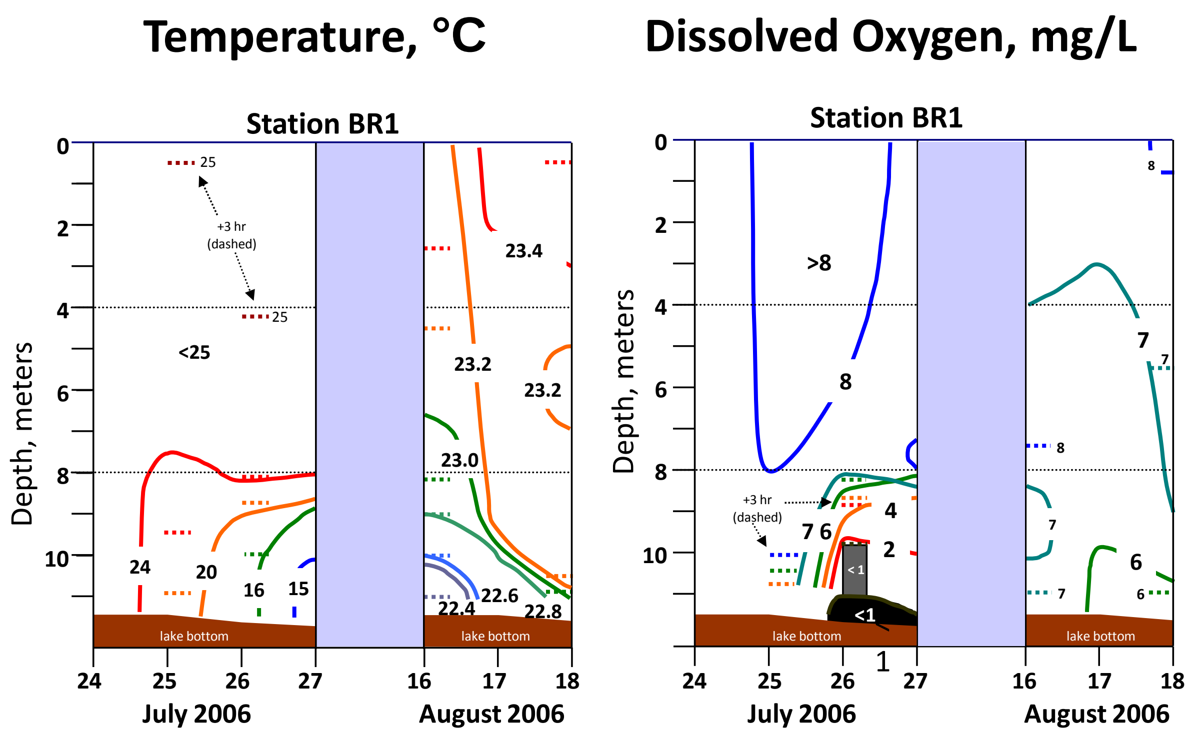

Figure 7. Depth-time diagrams of temperature and dissolved oxygen at Station BR1 in July and August 2006. Isopleths were hand-drawn and interpolated by eye. Where a second set of readings was obtained about three hours later on the same day (25 and 26 July, and 16 and 18 August), the isopleths are shown as interrupted dashed lines. Note that on 26 July, the thickness of the dead zone (<1 mg DO/L) increased by more than one meter within three hours.

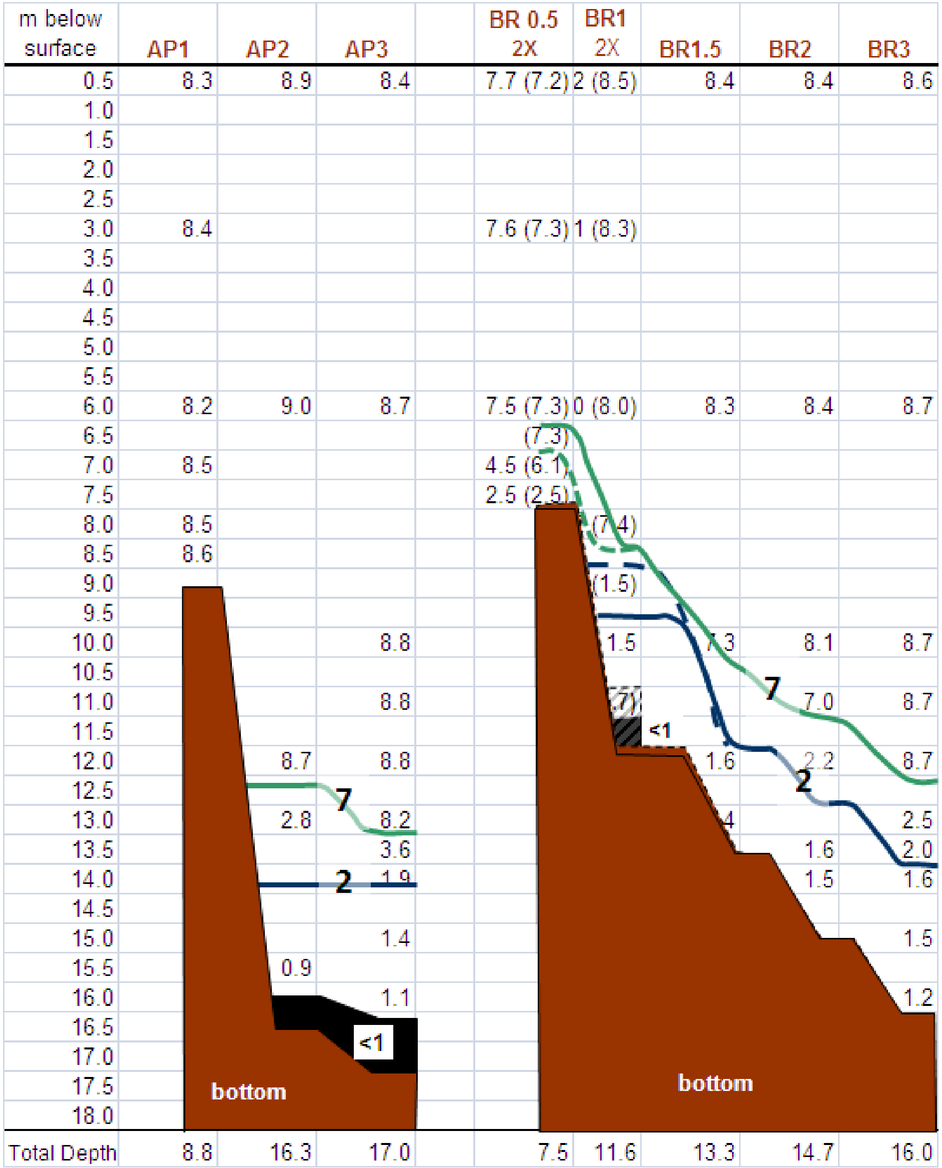

Figure 8. Isopleths of dissolved oxygen at 2 mg/L and 7 mg/L along transects AP and BR in on 26 July 2006. Regions of anoxia are shaded. Isopleths were hand-drawn and interpolated by eye. Where a second set of readings was obtained about three hours later at three stations along transect BR, the isopleths are shown as dashed lines.

assuming the same sediment oxygen demand (SOD) at both depths, and (2) the characteristics of the hypolimnion at SL15E are strongly influenced by the hypolimnion of the shallow (<15 m) Sandusky subbasin approximately 15 km to the southwest, which becomes hypoxic earlier than the rest of the central basin (Conroy 2007, Conroy *et al*., in preparation).

In all three years (figures 3 through 5), the thin hypolimnion in the shallow coastal water began to erode and disappear during our observation intervals, and it dissipated progressively lakeward and deeper. However, the time intervals were too brief to confirm that a hypolimnion did not reform or return to the study transects.

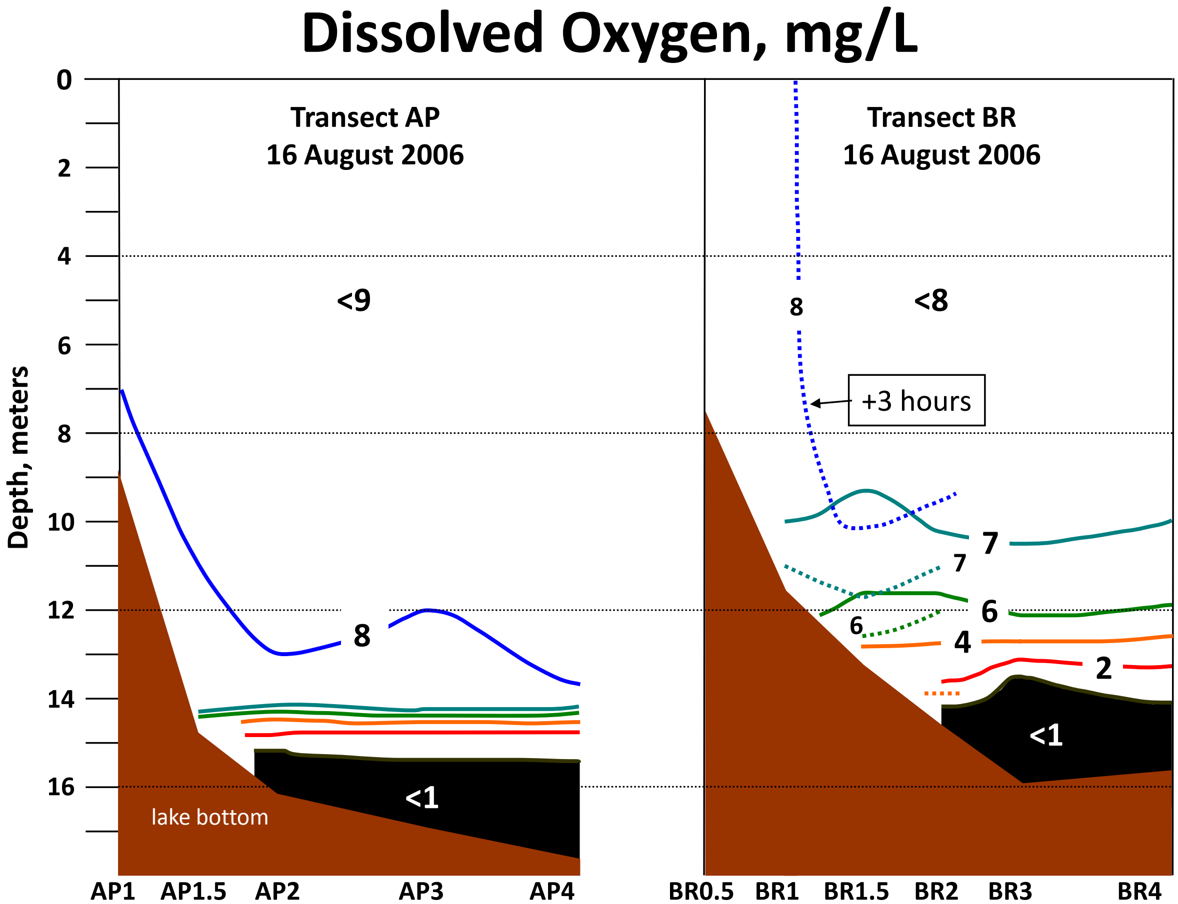

Figure 9. Isopleths of dissolved oxygen along transects AP and BR on 16 August 2006. Isopleths were hand-drawn and interpolated by eye. Where a second set of readings was obtained about three hours later at three stations along transect BR, the isopleths are shown as dashed lines.

Table 2. Frequency of occurrence (%) of bottom water hypoxia during sampling in July and August 2006 and 2007. When a station was sampled twice on the same day, only the first reading is included.

Station	AP1	AP1.5	AP2	AP3	AP4	BR0.5	BR1	BR1.5	BR2	BR3	BR4	BR5
2006												
days	6	4	6	5	3	5	7	5	6	4	4	0
% <4 mg/L	0	50	83	100	100	20	43	80	83	100	100	N/A
% <2 mg/L	0	50	83	100	100	0	29	40	50	100	75	N/A
% <1 mg/L	0	0	67	100	100	0	14	0	17	75	50	N/A
2007												
days	6	5	6	6	6	6	6	6	6	6	6	6
% <4 mg/L	50	80	83	83	67	33	83	100	83	100	83	100
% <2 mg/L	17	80	50	33	33	17	67	83	83	67	50	50
%<1 mg/L	0	20	0	0	0	0	17	33	17	0	0	0

The isolated patches of anoxic near-bottom water along the transects may have resulted from at least two mechanisms. First, the patches may represent parts of the hypolimnion of the deeper basin that were broken off by turbulence as an internal seiche wave "broke on shore" beneath the thermocline (Nguyen and Lamb 2008, Troy *et al*. 2008). Alternatively, variable sediment oxygen demand (SOD) from place to place on the lake bottom may result in variable rates of oxygen depletion in the overlying hypolimnion. An increase in SOD might arise locally, for example, from the influence of sewage effluents from nearby municipalities, as in this study from Lorain and the Cleveland metropolitan region to the east.

Some investigators have operationally defined the upper (and outer) limit of the hypolimnion to be at the 20 m contour (e.g., Burns *et al*. 2005), and this approximate depth may represent a physical limitation on hypolimnion depth in many areas of the Great Lakes (Rao 2008). Nevertheless, in the large area (50.0%) of the central basin shallower than 20 m, areas of anoxia in water as shallow as 11.5 m persist for several days or more (figures 3 and 4). The appearance of anoxia along both transects during our brief periods of observation both years suggests that these anoxia events are common every summer in areas <20 m deep. These events could be evidence of internal Kelvin waves and Poincaré waves that represent oscillations of the thermocline and can bring hypolimnetic water toward shore (Rao 2008). Seiche-induced upwellings of the hypolimnion induced by an internal seiche could transport anoxic water all the way to shore.

The duration of any single hypoxia event could determine which invertebrate taxa will survive and which ones will be extirpated until the next generation begins to colonize the area under conditions of sufficient oxygenation at an effective point of dispersal in the life cycle of the animal. Our data indicate that the effective upper limit of the central basin hypolimnion and accompanying anoxia is nearer 15 m than 20 m, at least some years (Figure 3 and appendix). The controlling influence of sporadic anoxia on zoobenthos community structure and productivity likely extends to even shallower depths, perhaps to the lake shore if upwellings occur with sufficient frequency on either shore. During our brief sampling intervals, near-bottom hypoxia (<2 mg/L) was never observed in 2006 at the most nearshore station on either transect and in 2007 only on 17% of the sampling days on Transect BR and never on Transect AP (Table 2). Anoxia (<1 mg/L) was not observed at the shallowest station (7.0 m, 8.5 m) on either transect in our study.

Our data present evidence that as the lake bottom rises toward shore, the top of the hypolimnion also rises, although the hypolimnion may become thinner (figures 5 and 8). That this relationship was not always observed (Figure 9) indicates that hypoxic water close to shore may be brought by Kelvin waves and internal seiches. In calm water this edge effect may in part result from depletion of DO by SOD in the thin hypolimnion near shore, giving the hypolimnion the shape of a saucer rather than a horizontal plane.

Wind set-up and barometric pressure differences over large lakes are known to establish surface and internal seiches and internal rotational effects such as Kelvin waves (Ludewig and Austin 2008, Nguyen and Lamb 2008, Rao 2008). Yet comparison of the timing of rapid changes in near-bottom DO concentrations (Figure 2) at the offshore stations in 2005 with concurrent or immediately preceding wind and wave directions and velocities (Figure 10) recorded at the NOAA buoy did not reveal a relationship. At the buoy, wave direction and velocity corresponded closely with wind direction and velocity. No wind data were available for the latter half of September, when fall turnover appeared to begin (Figure 2).

Wind direction in conjunction with distance from shore influenced on our sampling success. For example, strong southwest (offshore) winds throughout our sampling period in July 2006 permitted us to take measurements at the stations near shore but not further from shore (Figure 3) because of increasing wave heights progressively lakeward. The sudden appearance of the hypolimnion at Station BR1 on 25 July 2006 after none was present on 24 July and the thickening of the hypolimnion between 25 July and 26 July (Figure 6) indicates a partial upwelling of the hypolimnion and therefore its movement toward shore as a result of sustained strong southwest winds during the sampling period (Figure 10). Likewise, a period of strong winds from the north and northwest prevented sampling in late August 2006. The stations nearest shore were isothermal on 22 August (Figure 3), perhaps as a result of strong north winds during the immediately preceding three days (Figure 10) that would have depressed the epilimnion on the south shore

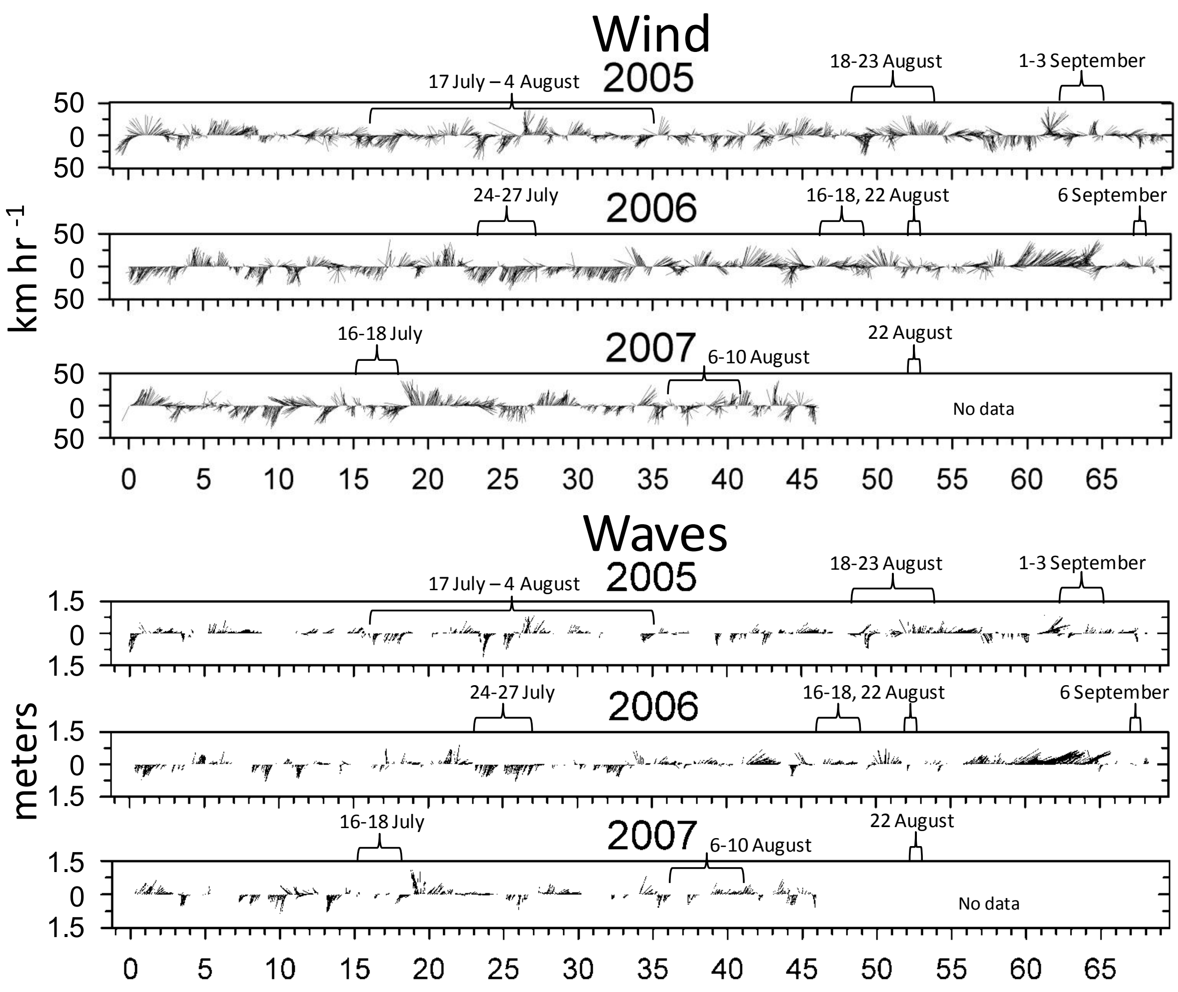

Figure 10. Hourly vector plots of wind direction and velocity and wave direction and height during the summers of 2005, 2006, and 2007 at NOAA buoy 45005 (Figure 1). X-axis is days since 1 July. Length of each vector represents velocity; compass orientation indicates the direction from which the wind and waves were traveling. Dates of events in 2005 discussed in the text are indicated, as are dates in 2006 and 2007 when DO profiles were taken on transects AP and BR. Data: NOAA National Data Buoy Center (www.ndbc.noaa.gov/station_page.php?station=45005).

of the lake. Prolonged strong winds from the northeast probably triggered the fall turnover observed in early September. Direct linkages between near-bottom DO concentration patterns and weather events in 2007 were not apparent.

A New Nearshore Hypoxia Metric for the Central Basin?

A large number of metrics and indicators have already been established to indicate trends in the ecosystem status of Lake Erie and the other Laurentian Great Lakes (OLEC 2004, US EPA 2007, LaMP 2008). Many of the metrics and indicators relate more or less directly to DO concentration because of the essential role of oxygen in the respiration and metabolic processes of plants, animals, and bacteria as well as the reduction-oxidation (redox) conditions of the bottom sediments that in turn affect internal nutrient loading potential. Yet, despite the recent attention to possible increases in anoxic “dead zones” in Lake Erie and other regions, such as the Gulf of Mexico (Rabalais *et al*. 2006), to our knowledge no agency has established a metric based on the frequency, extent, duration and severity of hypoxia and especially anoxia in Lake Erie, bays or basins of other Great Lakes, or estuaries and other coastal ocean regions. The Ambient Water Quality Indicator of the Lake Erie Quality Index (OLEC 2004) includes a Water Chemistry metric that is limited to concentrations of total phosphorus, total nitrate+nitrite, and total chloride. Lake Erie anoxia is addressed in a side-box in the State of the Lake Report (OLEC 2004, p. 6), but DO is not included as a component of the Water Chemistry metric or any other metric.

The animals living on the bottom of Lake Erie have long provided indirect clues to oxygen conditions in the three basins. The continued success of the burrowing mayfly (*Hexagenia* spp.) populations in the western basin is believed to hinge on the continuation of sufficient DO in summer near the sediment-water interface (Bridgeman *et al.* 2006). The species composition of the invertebrate communities living on and in the sediments indicates whether or not DO concentrations have declined to limiting levels during the life cycles of each species. Reduced numbers, restricted distributions, and the complete absence of animals susceptible to reduced DO concentrations, as well as increased abundances of those species highly tolerant of hypoxia or anoxia, are all indicators of DO conditions. An important point, however, is that even though DO concentrations may be sufficient to sustain a species most of a year, if the concentration drops below the threshold of tolerance for that species for only a brief period (from a few minutes to several weeks, depending on the species), that species will suffocate and disappear from the bottom invertebrate community. It then must recolonize the affected area to become re-established. The beginning of recolonization may yield a few rare specimens in sediment samples during periods of sufficient DO concentrations only to be followed by a period of extirpation if hypoxia or anoxia returns (Krieger 2005, 2006), and this cycle may be repeated in the central basin year after year. Thus, the invertebrate biota reveal clues as to preceding DO conditions, but species composition and abundance are also affected by other environmental factors, such as persistent toxic chemicals (Burns 1985), so that the invertebrate community may reflect a broad range of influences and not only DO.

Because of the value of benthic invertebrates as indicators of a broad suite of environmental factors, many of which are usually not recognized or measured directly, the abundances and proportions of the species comprising the zoobenthic community serve as the basis of several Great Lakes indicators. The Lake Erie 2008 Lakewide Management Plan (LaMP) Report includes “degradation of benthos” as an impaired use in central basin tributary, shoreland, nearshore and offshore waters, citing as evidence a degraded benthic community compared to that of reference conditions, dominant species indicative of a degraded environment, and keystone species such as unionid mussels and *Diporeia* amphipods that are absent or nearly so (LaMP 2008, p. 4-19). The report cites contaminated sediments, invasion of non-native species, and loss and degradation of habitat as the causes of impairment but does not specifically mention hypoxia as one of the causes. The abundance of *Hexagenia* mayflies is a component of the Key Indicator Species metric of the Biological Indicator of the Lake Erie Quality Index (LEQI) (Krieger 2004, OLEC 2004). That metric presently can only be applied to the western basin because these mayflies have not successfully recolonized the central basin except in very isolated locations (Krieger 2006). The distributions and abundances of mayflies, chironomid midges, and oligochaete worms in the western basin comprise three indicators of the Detroit River-Western Lake Erie Project (DR-WLEP; www.epa.gov/med/grosseile_site/indicators/). The State of the Great Lakes 2007 report (U.S. EPA 2007; www.epa.gov/solec/solec_2008/2/5_Erienotes.pdf) includes as indicators Benthos Diversity and Abundance – Aquatic Oligochaete Communities (Indicator #104) and *Hexagenia* (#122). Several recreationally and commercially valuable fish species (e.g., yellow perch) and the forage fishes upon which some of them feed depend partly or entirely on benthic invertebrates for food; thus, the condition of the fish community is tied directly to the invertebrate community that responds to DO conditions. Other indicators, such as algae blooms in the western basin (DR-WLEP), provide evidence of conditions that can lead to oxygen depletion in the central basin.

Even though neither DO concentration nor seasonal DO depletion is used as an explicit indicator or metric, the extent and rate of seasonal DO depletion has been monitored for many years by the U.S. EPA Great Lakes National Program Office (GLNPO). The monitoring network in the central basin consists of ten master stations that are visited five to six times yearly from early June through early to mid-September. The GLNPO monitoring program has effectively documented the rate of DO depletion in the hypolimnion and the presence of hypoxia and anoxia at individual stations (Figure 11). From these 10 stations, the extent of hypoxia and anoxia are extrapolated to other areas of the basin (Figure 12) based on interpolations of concentration values between stations (P. Bertram, USEPA GLNPO, personal communication 23 January 2009). The resulting maps, which show all regions where anoxia was detected at some time during the summer, indicate that anoxia tends to be more extensive in the western end than the eastern end of the basin, but it is apparent that anoxia extends eastward beyond the monitored area most years (Figure 12). The actual size and location of the region of anoxia (dead zone) observed during any one cruise are usually smaller than the summary map for all cruises that year (Figure 12) and are probably determined in part by relocations of the anoxic water mass throughout summer resulting from the internal dynamics of the basin (P. Bertram, USEPA GLNPO, personal communication 23 January 2009).

GLNPO has restricted representation of the region of anoxia to the 20 m contour or deeper (Figure 12) because their sampling program does not include stations in shallower water (P. Bertram, USEPA GLNPO, personal communication 23 January 2009). Our data for both the western and southern margins of the basin clearly show that the region of anoxia sometimes extends to the 15 m contour or shallower (e.g., figures 2, 3, 6, 8), thereby including 50% more of the lake bottom in the basin than is circumscribed by the 20 m contour, for a total of 75% of the basin. Therefore, although the GLNPO monitoring program supplies important information regarding DO depletion in the westernmost three-fourths of the central basin within the 20 m contour (less than 50% of the basin area), the data interpretation is conservative and neglects an equal area of the basin that is shallower than 20 m.

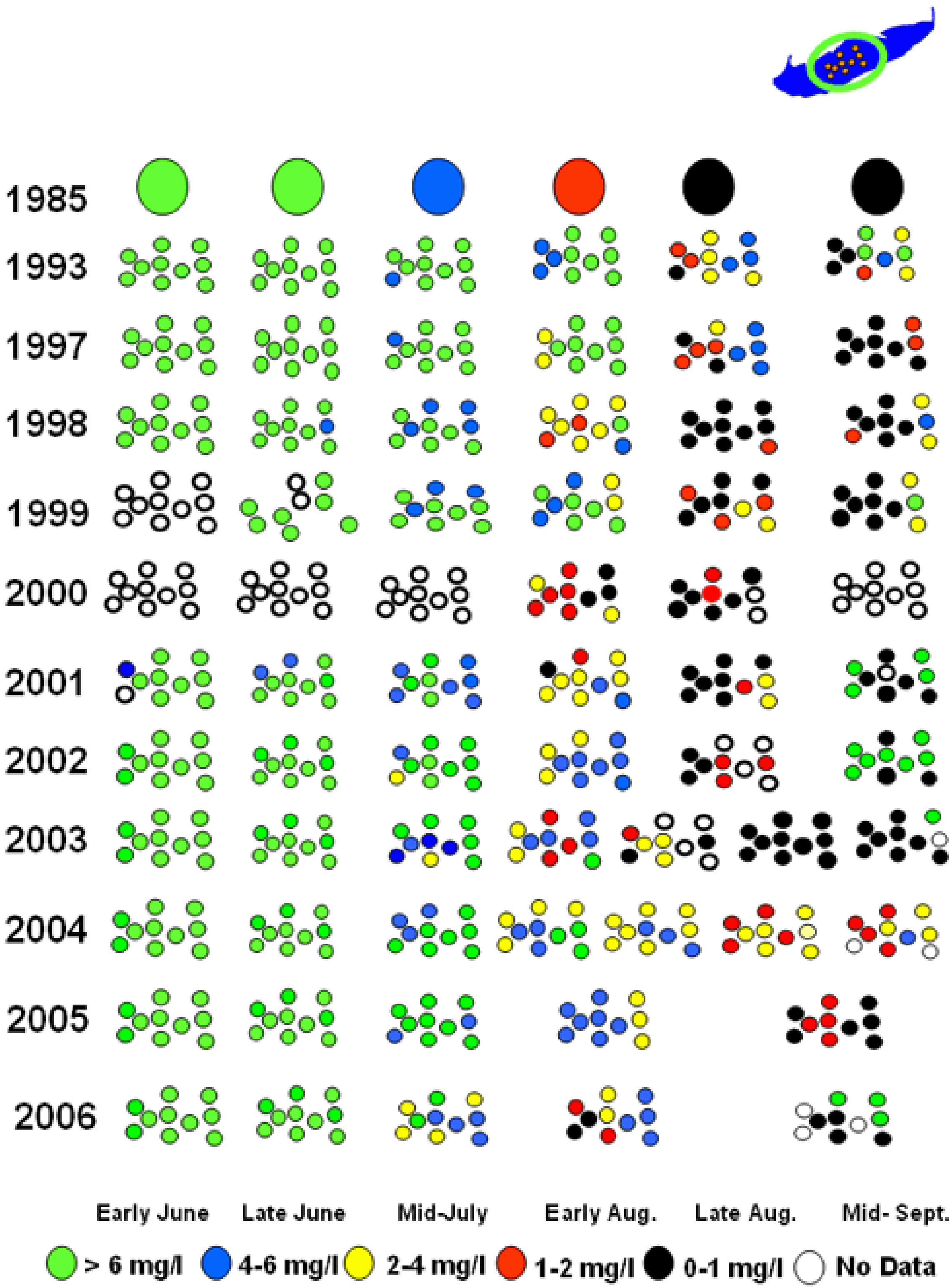

Figure 11. Ten master stations in the central basin sampled for water chemistry by USEPA GLNPO most years from early June through mid-September, 1985-2006. Colors indicate ranges of dissolved oxygen concentrations found at station on each visit; red and black indicate hypoxia and anoxia, respectively. Source: www.epa.gov/glnpo/glindicators/water/oxygenb.html

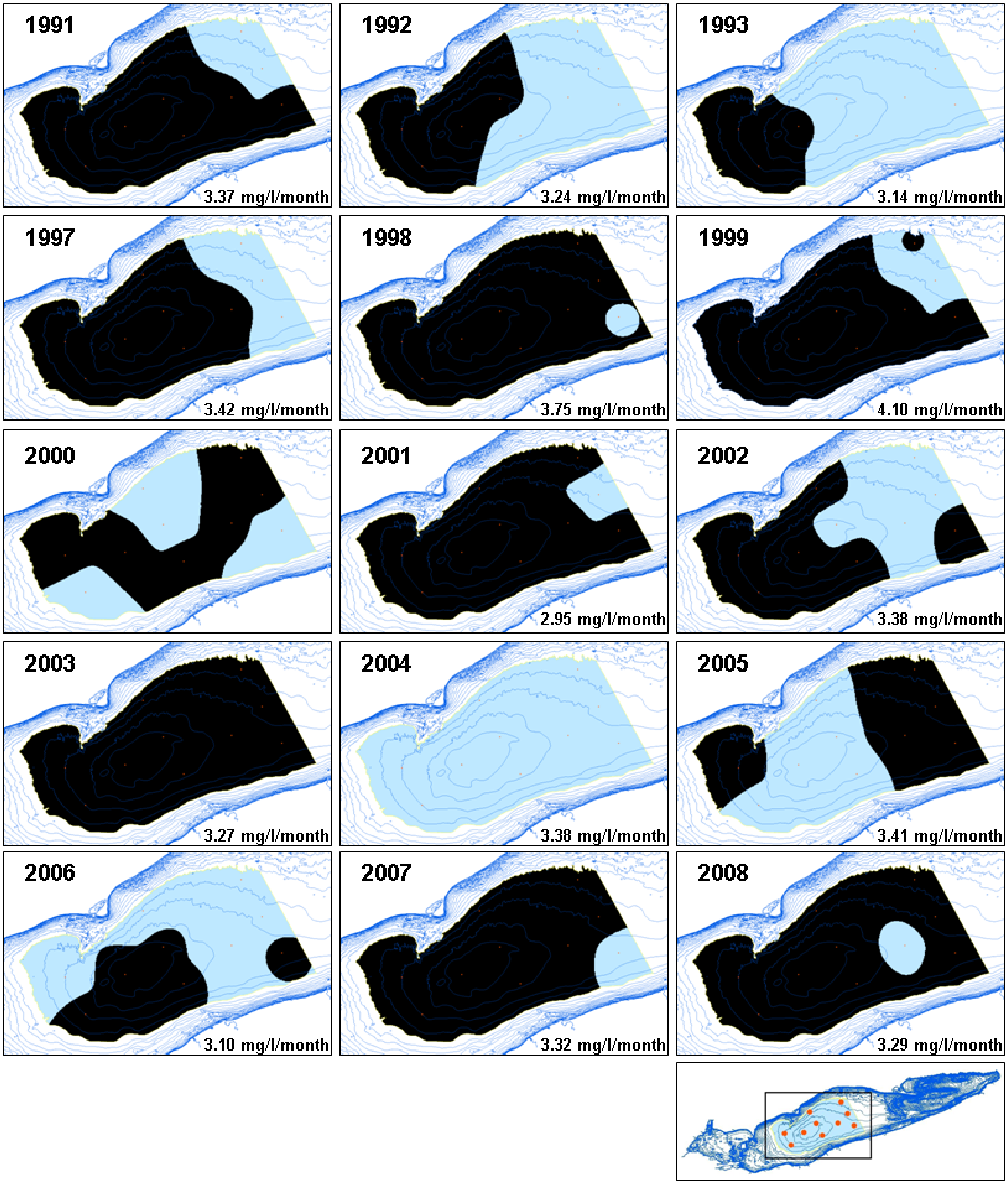

Figure 12. Maximum extent of the dead zone (black areas), or region of anoxia (DO ≤1 mg/L), in summer most years from 1991 through 2008 as extrapolated by U.S. EPA GLNPO to the 20 meter contour from DO concentrations measured at the ten stations shown in the graphic at lower right (Graphic created by Jeff May; courtesy of Paul Bertram, U.S. EPA Great Lakes National Program Office).

As discussed above, distributions and abundances of benthic invertebrate species in regions of the central basin shallower than 20 m strongly indicate that severe oxygen depletion has led to degradation of that community, but actual data showing that DO depletion actually occurs in those areas are generally lacking. Certainly, community composition cannot enlighten us about the timing, duration, extent and severity of anoxia events, only that such events have probably taken place. Therefore, DO data collected during the period of thermal stratification in the regions of the basin shallower than 20 m are desirable.

DO concentrations in areas of the central basin <20 m deep have been collected for many years by some agencies. Ohio DNR measures DO within a foot (0.30 m) of the lake bottom from May through September at 40 stations in US waters of the western basin and westernmost central basin. Those data, which have been archived electronically, have revealed low DO east of the island area, particularly east of Kelleys Island in the Sandusky subbasin (J. Tyson, Ohio DNR, personal communication, 12 December 2008). The Ontario Ministry of Natural Resources (OMNR) has maintained a sampling program at fixed stations in the central basin where samples are collected from mid-August to October; the sampling period was designed, however, to avoid the period of central basin hypoxia. OMNR also measures DO profiles at four stations in the western central basin from early May to mid-October. OMNR recently centralized over 34,000 physicochemical records including DO from agencies in Ohio, Michigan, New York and Ontario spanning four decades, although records of near-bottom sample depth may not be precise in many cases (T. Johnson, OMNR, personal communication, 12 December 2008). These and other data sets could be mined to detect periods of hypoxia at particular stations.

Another potential source of information might be water quality records maintained by water treatment plants at water intakes offshore of Lake Erie (e.g., Lorain, Cleveland, Sandusky, Ashtabula). Operators of three of the four water treatment plants in Cleveland measure DO daily during the summer stratification period. The intake pipes are located at depths of 7.6-10.6 m below the surface and well above the lake bottom and therefore do not often encounter hypoxic hypolimnion water (most recently in 2006; M. Rogers, Cleveland Division of Water, personal communication, 28 January 2009). The availability of routine DO measurements at water intakes might provide a cost-effective means of revealing low DO concentrations of varying duration at the elevations of the individual water intakes, assuming the intakes lie within or near the upper boundary of the hypolimnion.

A hypoxia metric would provide maximum insights into the physical mechanisms of DO variation if DO (and temperature) measurements were coordinated among agencies so that measurements are taken on both sides of the basin on the same days and hours (as weather permits) at the same depth contours using identical methodologies. The sampling protocol and station density and locations should be determined in consultation with modelers in order to maximize the potential value to modeling efforts. Further, measurements should be coordinated with cruises of GLNPO's *R/V Lake Guardian* in order to integrate data from shallow coastal waters with data from open lake, deep water stations.

Specific criteria upon which a hypoxia metric could be scored annually also would need to be developed by collaborating agencies. Criteria could include one or a combination of parameters. Some possible parameters are the percentage of shallow (<20 m deep) stations where hypoxia occurs at some time during stratification, average frequency of hypoxia at all stations shallower than a designated depth during stratification (e.g., Table 2), and average DO concentration of stations in different regions of the station network during stratification.

In summary, a new hypoxia metric would provide the following advantages:
1. Direct measurement of the timing, duration, extent and severity of hypoxia events at designated stations.
2. Direct evidence to support explanations of degraded zoobenthic communities in shallow (<20 m) regions of the central basin.
3. A numerical basis for monitoring year-to-year changes in areal extent, duration and severity of hypoxia and anoxia in shallow regions of the basin, and thus trends toward improvement or further degradation over time.
4. Supplemental data to assist the calibration and validation of hypoxia models for the central basin being developed NOAA GLERL and others.

Potential disadvantages of a new hypoxia metric include:
1. Another set of data to be collected while performing other functions aboard research vessels, or possibly additional cruises for the sole purpose of collecting the DO data.
2. Another set of data to be computerized, maintained and analyzed by agency staff.
3. Desirability of collecting data simultaneously along the north and south shores and western end of the basin.
4. Need to apply identical sampling methods across agencies.

Information Dissemination

Preliminary results of this project were presented at the Fifty-first Annual Conference on Great Lakes Research of the International Association for Great Lakes Research held at Trent University in Peterborough, Ontario, 19-23 May 2008. The platform presentation on Friday, 23 May, was titled "Nearshore Hypoxia in Lake Erie's Central Basin: a Proposed Lake Quality Indicator". Selected results of this project were also presented on 21 October 2008 as a PowerPoint presentation to staff members of SAIC, Inc. in Springfield, Ohio. We are in the process of preparing a manuscript based on this project for submission to a peer-reviewed scientific journal.

Acknowledgments

The authors gratefully acknowledge the assistance of several colleagues whose help made this project successful. Foremost is Bill Edwards, USGS, who skillfully piloted the *R/V Bowfin* and geolocated the stations, and who also assisted in collection and interpretation of the data. Anne Stearns, NCWQR, performed quality assurance tests of the accuracy of the several DO meters, assisted in the field, and assisted with data analysis. Student technicians Chris Boehler and Kristi Thomas at the NCWQR, Heidelberg University, assisted in data collection. Jakob Boehler was of crucial assistance in creating and formatting the wind and wave graphs. Matt Thomas of Ohio Sea Grant and the F. T. Stone Laboratory of The Ohio State University, graciously provided sonde data for temperature and DO from two buoys stationed in the central basin in 2005. The NCWQR provided additional matching funds for completing the final report.

Literature Cited

Bartish, T. 1987. A review of exchange processes among the three basins of Lake Erie. *J. Great Lakes Res*. 13:607-618.

Bedford, K.W. 1992. The physical effects of the Great Lakes on tributaries and wetlands, a summary. *J. Great Lakes Res*. 18:571-589.

Bridgeman, T.B., D.W. Schloesser, and A.E. Krause. 2006. Recruitment of *Hexagenia* mayfly nymphs in western Lake Erie linked to environmental variability. *Ecological Applications* 16:601-611.

Britt, N.W. 1955. *Hexagenia* (Ephemeroptera) population recovery in western Lake Erie following the 1953 catastrophe. *Ecology* 36:520-522.

Burns, N.M. 1985. *Erie, the lake that survived*. Rowman & Allanheld Publ., Totawa, New Jersey.

Burns, N.M., D.C. Rockwell, P.E. Bertram, D.M. Dolan, and J.H. Ciborowski. 2005. Trends in temperature, secchi depth, and dissolved oxygen depletion rates in the central basin of Lake Erie, 1983-2002. *J. Great Lakes Res*. 31 sSuppl. 2):35-49.

Conroy, J.D. 2007. Testing the Algal Loading Hypothesis: the importance of Sandusky River phytoplankton inputs to offshore Lake Erie processes. Ph.D. dissertation. The Ohio State University, Columbus, Ohio.

Conroy, J.D., D.D. Kane, E.L. Quinlan, M.A. Thomas, W.J. Edwards, and D.A. Culver. In preparation. Remediating and managing for ecosystem impairments: understanding the relative importance of human-derived effects and natural processes on hypolimnetic hypoxia in Lake Erie.

Effler, S.W., B.A. Wagner, S.M. O'Donnell, D.A. Matthews, D.M. O'Donnell, R.K. Gelda, C.M. Matthews, and E.A. Cowen. 2004. An upwelling event at Onondaga Lake, NY: characterization, impact, and recurrence. *Hydrobiologia* 511:185-199.

Kalff, J. 2002. *Limnology, inland water ecosystems.* Prentice Hall, Upper Saddle River, New Jersey. 592 pp.

Krieger, K.A. 1984. Benthic macroinvertebrates as indicators of environmental degradataion in the southern nearshore zone of the central basin of Lake Erie. *J. Great Lakes Res*. 10:197-209.

Krieger, K.A. 2004. *Mayfly metric of the Lake Erie Quality Index: design of an efficient censusing program, data collection, and development of the metric*. Final Rept. to Ohio Lake Erie Commission. Grant LEQI 01-03.

Krieger, K.A. 2005. *Mayflies and zebra/quagga mussels in Lake Erie's central basin surveyed with a remotely operated vehicle*. Final Report to Ohio Lake Erie Commission. Project SG 232-04.

Krieger, K.A. 2006. *Characterization of mayfly (*Hexagenia*) population refugia in the central basin of Lake Erie*. Final Report to Ohio Lake Erie Commission. Project SG 254-05.

Krieger, K.A., and L.S. Ross. 1993. Changes in the benthic macroinvertebrate community of the Cleveland Harbor area of Lake Erie from 1978 to 1989. *J. Great Lakes Res*. 19:237-249.

LaMP. 2008. *2008 Lakewide Area Management Plan (LaMP) Report*. Lake Erie LaMP Management Committee, Environment Canada and U.S. Environmental Protection Agency. www.epa.gov/greatlakes/lamp/le_2008/index.html.

Ludewig, B.G., and J.A. Austin. 2008. *Upwelling in idealized stratified lakes*. 51st Annual Conference on Great Lakes Research, International Association for Great Lakes Research, 19-23 May 2008, Peterborough, Ontario. (Abstract)

Nguyen, V.T., and K.G. Lamb. 2008. *Numerical simulation of nonlinear internal waves generated by wind forcing over a surface of Lake Erie*. 51st Annual Conference on Great Lakes Research, International Association for Great Lakes Research, 19-23 May 2008, Peterborough, Ontario. (Abstract)

OLEC. 2004. *State of the Lake Report 2004 Lake Erie Quality Index*. Ohio Lake Erie Commission, Toledo, Ohio.

Rabalais, N.N., R.E. Turner, B.K. Sen Gupta, D.F. Boesch, P. Chapman, and M.C. Murrell. 2006. Characterization and long-term trends of hypoxia in the northern Gulf of Mexico: Does the science support the action plan? *Estuaries and Coasts* 30(5):753-772.

Rao, Y.R. 2008. Coastal physical processes in the Great Lakes. *Verh. Internat. Verein. Limnol*. 30:638-642.

Richards, R.P. 1981. *Chemical limnology in the nearshore zone of Lake Erie between Vermilion, Ohio and Ashtabula, Ohio, 1978-1979: data summary and preliminary interpretations*. + appendix. Final Report on Lake Erie Nearshore Study, USEPA, GLNPO, Chicago, Illinois.

Royer, L., P.F. Hamblin, and F.M. Boyce. 1987. A comparison of drogues, current meters, winds, and a vertical profiler in Lake Erie. *J. Great Lakes Res*. 13:578-586.

Schloesser, D.W., K.A. Krieger, J.J.H. Ciborowski, and L.D. Corkum. 2000. Recolonization and possible recovery of burrowing mayflies (Ephemeroptera: Ephemeridae: *Hexagenia* spp.) in Lake Erie of the Laurentian Great Lakes. *J. Aquatic Ecosystem Stress and Recovery.* 8:125-141.

Systat Software, Inc. 2008. *SigmaPlot® 11.0 User's Guide.* San Jose, California.

Troy, C.D., E.L. Hult, and J.R. Koseff. 2008. *Richardson number measurements in breaking internal waves*. 51st Annual Conference on Great Lakes Research, International Association for Great Lakes Research, 19-23 May 2008, Peterborough, Ontario. (Abstract)

U.S. EPA. 2007. *State of the Great Lakes 2007*. EPA 905-R-07-003. U.S. Environmental Protection Agency and Environment Canada.

Appendix

Data Collected as Part of This Grant

16 July 2007	mg/L					Temperature				
Depth, m	AP1	AP2	AP3	AP4	AP5	AP1	AP2	AP3	AP4	AP5
0.0										
0.5	9.5	8.4	7.1	8.5	9.0	23.1	22.2	22.8	22.2	22.4
1.0										
1.5										
2.0										
2.5										
3.0	9.0	10.4	10.5	9.6	8.7	22.9	22.0	22.4	21.9	21.9
3.5										
4.0										
4.5										
5.0										
5.5										
6.0	7.5	9.5	6.3	9.3	9.4	22.4	22.0	22.1	21.8	21.8
6.5	5.4					22.2				
7.0	4.8					22.1				
7.5	4.4					22.1				
8.0	3.8					22.0				
8.5	3.6					22.0				
9.0		5.5	3.6	6.3	9.0		21.9	21.9	21.8	21.8
9.5										
10.0		4.7	3.5				21.9	21.8		
10.5										
11.0			3.4					21.8		
11.5										
12.0		4.0	3.4	5.3	5.0		21.9	21.8	21.8	21.7
12.5										
13.0		3.6	3.3				21.8	21.8		
13.5										
14.0		3.1	3.2				20.1	21.8		
14.5										
15.0		1.0	3.6	4.7	4.1		14.3	15.0	21.0	21.4
15.5		0.9					14.3			
16.0			3.6	4.6				14.4	12.1	
16.5			3.4					14.2		
17.0				4.4					12.2	
17.5				4.1					12.1	
18.0					4.2					11.5
Total										
Depth, m	8.8	16.1	16.8	17.5	18.5	8.8	16.1	16.8	17.5	18.5
start time	10:05	10:30	11:00	11:26	11:49	10:05	10:30	11:00	11:26	11:49

16 July 2007	mg/L							Temperature						
Depth, m	BR0.5	BR1	BR1.5	BR2	BR3	BR4	BR5	BR0.5	BR1	BR1.5	BR2	BR3	BR4	BR5
0.0														
0.5	8.5	8.8	8.8	8.8	8.7	8.7	8.7	24.4	24.2	23.7	23.6	23.3	22.6	23.1
1.0														
1.5														
2.0														
2.5														
3.0	8.3	9.6	9.1	8.9	8.7	8.9	9.3	23.3	23.4	23.3	23.0	22.7	22.5	22.5
3.5														
4.0														
4.5														
5.0	7.8							23.2						
5.5														
6.0	7.8	9.4	9.1	9.3	8.9	9.0	10.0	23.1	23.1	23.0	22.8	22.6	22.3	22.4
6.5	7.8							23.1						
7.0														
7.5														
8.0														
8.5														
9.0		9.1	9.2	9.3	9.0	9.3	9.0		23.0	22.9	22.6	22.5	22.3	22.4
9.5		9.1							23.0					
10.0		9.1							22.9					
10.5		8.7							22.9					
11.0		7.8	9.0						22.7	22.7				
11.5														
12.0			5.0	9.0	8.9	9.2	7.5			20.0	22.3	22.3	22.2	22.3
12.5			0.4							15.6				
13.0				3.2	8.7	9.1					19.3	22.3	22.1	
13.5				0.3		9.0					15.2		22.0	
14.0				0.3	1.6	9.0	6.7				15.1	15.8	21.9	22.2
14.5														
15.0					1.3	1.5	5.8					15.4	14.9	19.6
15.5					1.1							15.4		
16.0							2.0							14.3
16.5							1.8							14.2
17.0														
17.5														
18.0														
Total														
Depth, m	7	11.5	13.1	14.6	15.7	15.5	16.6	7	11.5	13.1	14.6	15.7	15.5	16.6
start time	14:20	14:15	14:02	13:50	13:32	13:16	13:00	14:20	14:15	14:02	13:50	13:32	13:16	13:00

17 July 2007	mg/L				Temperature			
Depth, m	AP1	AP2	AP3	AP4	AP1	AP2	AP3	AP4
0.0								
0.5	7.9	8.8	9.0	9.0	23.0	22.9	22.1	22.0
1.0								
1.5								
2.0								
2.5								
3.0	9.3	9.9	9.0	8.9	23.0	22.8	22.1	22.0
3.5								
4.0								
4.5								
5.0								
5.5								
6.0	8.3	9.6	10.0	9.8	23.0	22.5	22.1	21.9
6.5								
7.0	7.5				22.7			
7.5								
8.0	7.0				22.3			
8.5	6.5				22.3			
9.0		3.9	8.8	8.9		22.0	22.0	21.9
9.5								
10.0		3.2				22.0		
10.5								
11.0		2.9				21.9		
11.5								
12.0		2.7	5.3	7.5		21.9	21.9	21.7
12.5								
13.0		2.6	4.5			21.8	21.8	
13.5								
14.0		1.1	4.1			16.1	21.3	
14.5								
15.0		1.2	4.1	6.7		13.4	12.3	14.0
15.5		1.2				13.3		
16.0		1.2	3.8	6.0		13.3	12.1	11.5
16.5			3.7				12.1	
17.0				5.4				11.4
17.5								
18.0								
Total Depth, m	8.9	16.2	17	17.5	8.9	16.2	17	17.5
time	11:11	11:25	11:40	11:55	11:11	11:25	11:40	11:55

17 July 2007	mg/L							Temperature						
Depth, m	BR0.5	BR1	BR1.5	BR2	BR3	BR4	BR5	BR0.5	BR1	BR1.5	BR2	BR3	BR4	BR5
0.0														
0.5	8.4	9.0	8.9	9.0	9.0	9.0	8.7	23.2	23.0	22.4	22.3	22.2	22.3	22.5
1.0														
1.5														
2.0														
2.5														
3.0	9.5	9.0	9.0	9.1	9.0	9.1	9.3	23.2	23.0	22.3	22.3	22.2	22.3	22.5
3.5														
4.0														
4.5														
5.0	8.8							23.2						
5.5														
6.0	8.1	9.4	9.3	9.3	9.3	9.4	9.8	23.2	23.0	22.3	22.3	22.2	22.2	22.4
6.5	7.8							23.1						
7.0	4.5							22.8						
7.5														
8.0														
8.5														
9.0		9.3	9.2	9.4	9.5	9.5	9.6		22.5	22.0	22.0	22.1	22.0	22.1
9.5														
10.0		1.0							17.6					
10.5		0.6							15.8					
11.0		0.4	8.6						15.7	21.3				
11.5														
12.0			1.4	9.2	9.5	9.4	9.5			15.5	21.5	22.0	21.9	22.1
12.5			0.8							15.4				
13.0				2.0							15.5	22.0		21.9
13.5				1.2							15.4			
14.0				1.0	9.2	9.3					15.4	21.7	21.7	
14.5					2.4	5.1						15.2	14.5	
15.0					2.0	2.4	5.6					14.9	14.1	17.2
15.5					1.9		3.5					14.9		13.6
16.0							3.2							13.5
16.5							3.0							13.5
17.0														
17.5														
18.0														
Total Depth, m	7.3	11.6	13.2	14.6	15.8	15.5	16.7	7.3	11.6	13.2	14.6	15.8	15.5	16.7
time	14:00	13:50	13:35	13:25	13:10	12:55	12:35	14:00	13:50	13:35	13:25	13:10	12:55	12:35

18 July 2007	mg/L							Temperature						
Depth, m	BR0.5	BR1	BR1.5	BR2	BR3	BR4	BR5	BR0.5	BR1	BR1.5	BR2	BR3	BR4	BR5
0.0														
0.5	8.3	9.2	9.4	9.4	9.5	9.5	9.6	23.5	23.2	23.2	22.7	22.1	22.1	22.1
1.0														
1.5														
2.0														
2.5														
3.0	8.3	9.0	9.2	9.9	10.5	11.1	12.1	23.1	22.9	22.8	22.4	22.0	22.0	22.1
3.5														
4.0	8.5							23.1						
4.5														
5.0	8.6							23.0						
5.5														
6.0	9.4	10.1	10.6	11.9	11.9	11.8	12.7	22.8	22.8	22.7	22.3	21.9	21.9	22.0
6.5	8.8							22.7						
7.0														
7.5														
8.0														
8.5														
9.0		7.9	11.2	9.0	11.6	8.3	7.9		20.6	22.6	22.3	21.9	21.9	21.9
9.5														
10.0		1.8							15.7					
10.5		1.4							15.5					
11.0		1.0	2.4						15.5	16.7				
11.5														
12.0			1.9	5.4	9.6	4.6	5.6			15.4	21.2	21.9	21.9	21.9
12.5			1.6							15.3				
13.0				3.6	8.0	3.5					14.7	21.7	21.8	
13.5				2.2							14.7			
14.0				1.8	3.9	3.1	4.1				14.7	14.2	14.0	21.8
14.5					3.3	2.5						13.8	13.5	
15.0					2.7	2.2	3.8					13.8	13.5	20.2
15.5					2.5		3.3					13.8		13.1
16.0							3.0							13.0
16.5														
17.0														
17.5														
18.0														
Total														
Depth, m	7.1	11.5	13.2	14.6	15.9	15.5	16.6	7.1	11.5	13.2	14.6	15.9	15.5	16.6
start time	12:24	12:14	12:04	11:50	11:38	11:25	11:08	12:24	12:14	12:04	11:50	11:38	11:25	11:08

18 July 2007	mg/L					Temperature				
Depth, m	AP1	AP1.5	AP2	AP3	AP4	AP1	AP1.5	AP2	AP3	AP4
0.0										
0.5	9.0	9.4	9.6	9.2	9.4	23.5	23.7	23.3	22.9	22.6
1.0										
1.5										
2.0										
2.5										
3.0	9.1	9.4	9.4	9.4	9.6	22.9	22.7	22.2	22.1	22.0
3.5										
4.0										
4.5										
5.0										
5.5										
6.0	9.0	10.3	10.4	10.8	11.0	22.3	22.3	22.0	22.0	21.9
6.5										
7.0	9.1					22.2				
7.5	9.1					22.2				
8.0	8.9					22.2				
8.5										
9.0		10.6	11.2	11.1	11.2		22.2	22.0	21.9	21.8
9.5										
10.0										
10.5										
11.0										
11.5										
12.0		6.3	10.9	10.2	6.8		19.7	21.9	21.9	21.8
12.5										
13.0		1.6					14.4			
13.5										
14.0		1.4	3.9		5.9		13.8	13.4		21.7
14.5										
15.0			4.0	7.1	5.7			12.5	11.6	11.5
15.5			3.9	6.4				12.5	11.5	
16.0				5.9	5.2				11.5	11.3
16.5				5.4	4.8				11.5	11.2
17.0					4.5					11.2
17.5										
18.0										
Total										
Depth, m	8.7	14.6	16.2	16.9	17.6	8.7	14.6	16.2	16.9	17.6
start time	13:55	13:45	13:35	13:20	13:03	13:55	13:45	13:35	13:20	13:03

6 August 2007 mg/L (1st trial)

Depth, m	AP1	AP1.5	AP2	AP3	AP4
0.0					
0.5	8.5	8.4	8.4	8.5	10.0
1.0					
1.5					
2.0					
2.5					
3.0	6.0	8.4	9.0	8.0	7.1
3.5					
4.0					
4.5					
5.0					
5.5					
6.0	4.4	3.6	4.1	3.9	3.3
6.5					
7.0	3.3				
7.5					
8.0	3.3				
8.5	3.3				
9.0		3.3	3.6	2.6	1.8
9.5					
10.0					
10.5					
11.0					
11.5					
12.0		3.0	3.4	2.4	1.4
12.5					
13.0		2.7			
13.5		2.2			
14.0		1.6			
14.5			2.6		
15.0			2.1	2.4	1.7
15.5			1.9	2.2	
16.0				2.1	1.6
16.5				2.0	1.6
17.0					1.5
17.5					
18.0					
Total Depth, m	8.8	14.5	16.1	16.8	17.4
Start time	10:15	10:40	11:04	11:30	11:50

6 August 2007 Temperature

Depth, m	AP1	AP1.5	AP2	AP3	AP4
0.0					
0.5	24.2	24.2	23.8	23.8	24.0
1.0					
1.5					
2.0					
2.5					
3.0	24.2	24.1	23.8	23.7	23.9
3.5					
4.0					
4.5					
5.0					
5.5					
6.0	24.1	24.1	23.7	23.7	23.8
6.5					
7.0	22.9				
7.5					
8.0	22.5				
8.5	22.3				
9.0		24.0	23.7	23.7	23.8
9.5					
10.0					
10.5					
11.0					
11.5					
12.0		22.0	23.1	23.1	23.8
12.5					
13.0		20.3			
13.5		18.6			
14.0		15.8			
14.5			14.6		
15.0			14.4	13.0	14.0
15.5			14.4	12.8	
16.0				12.8	11.8
16.5				12.8	11.7
17.0					11.7
17.5					
18.0					
Total Depth, m	8.8	14.5	16.1	16.8	17.4
Start time	10:15	10:40	11:04	11:30	11:50

6 August 2007 mg/L

Depth, m	BR0.5	BR1	BR1.5	BR2	BR3	BR4	BR5
0.0							
0.5	8.3	8.2	8.5	8.4	8.5	9.2	10.6
1.0							
1.5							
2.0							
2.5							
3.0	8.1	8.2	8.5	8.6	8.8	9.3	4.3
3.5							
4.0							
4.5							
5.0	8.4						
5.5							
6.0	4.2	9.0	9.6	3.5	3.5	5.0	3.0
6.5	3.6						
7.0							
7.5							
8.0							
8.5							
9.0		2.9	1.9	2.1	2.5	2.8	2.0
9.5							
10.0		1.7					
10.5		1.5					
11.0		1.3					
11.5			1.7				
12.0			1.5	1.7	1.9	2.1	1.6
12.5			1.3				
13.0				1.5			
13.5				1.4			
14.0				1.4			
14.5					1.7	1.8	
15.0					1.6	1.6	1.7
15.5					1.6		1.7
16.0							1.6
16.5							
17.0							
17.5							
18.0							
Total Depth, m	7.1	11.5	13.1	14.5	15.9	15.5	16.4
Start time	14:04	13:55	13:41	13:30	13:13	13:02	12:45

6 August 2007 Temperature

Depth, m	BR0.5	BR1	BR1.5	BR2	BR3	BR4	BR5
0.0							
0.5	24.8	25.2	24.6	24.5	24.1	24.2	24.0
1.0							
1.5							
2.0							
2.5							
3.0	24.3	24.3	24.1	23.8	23.8	23.8	23.7
3.5							
4.0							
4.5							
5.0	24.1						
5.5							
6.0	24.0	24.0	24.0	23.7	23.7	23.7	23.6
6.5	24.0						
7.0							
7.5							
8.0							
8.5							
9.0		21.5	23.8	23.7	23.7	23.7	23.6
9.5							
10.0		18.7					
10.5		18.3					
11.0		18.1					
11.5			18.0				
12.0			17.5	19.8	23.1	23.5	23.6
12.5			17.5				
13.0				17.3			
13.5				17.3			
14.0				17.3			
14.5					17.8	18.0	
15.0					17.7	17.9	19.7
15.5					17.7		17.6
16.0							16.9
16.5							
17.0							
17.5							
18.0							
Total Depth, m	7.1	11.5	13.1	14.5	15.9	15.5	16.4
Start time	14:04	13:55	13:41	13:30	13:13	13:02	12:45

6 August 2007	mg/L	(2nd trial)			
Depth, m	AP1	AP1.5	AP2	AP3	AP4
0.0					
0.5	8.6	9.0	8.3	8.3	8.4
1.0					
1.5					
2.0					
2.5					
3.0	8.5	8.6	8.3	8.1	8.8
3.5					
4.0					
4.5					
5.0					
5.5					
6.0	8.6	9.4	9.0	4.5	2.6
6.5					
7.0	6.6				
7.5	3.0				
8.0	2.6				
8.5					
9.0			9.2	2.2	1.8
9.5					
10.0					
10.5					
11.0					
11.5					
12.0		1.9	3.2	1.7	1.6
12.5					
13.0		1.7			
13.5		1.2			
14.0		1.0	2.3		
14.5					
15.0			1.9	1.9	2.0
15.5			1.7	1.7	
16.0				1.7	2.0
16.5				1.6	2.0
17.0					1.9
17.5					
18.0					
Total					
Depth, m	8.5	14.6	16	16.8	17.5
Start time	15:21	15:09	15:03	14:46	14:35

6 August 2007	Temperature				
Depth, m	AP1	AP1.5	AP2	AP3	AP4
0.0					
0.5	25.3	24.8	24.7	24.8	24.6
1.0					
1.5					
2.0					
2.5					
3.0	24.4	24.3	23.9	23.9	24.0
3.5					
4.0					
4.5					
5.0					
5.5					
6.0	24.1	24.2	23.8	23.8	23.9
6.5					
7.0	23.9				
7.5	23.5				
8.0	22.5				
8.5					
9.0			23.7	23.8	23.8
9.5					
10.0					
10.5					
11.0					
11.5					
12.0		21.5	23.5	22.5	23.8
12.5					
13.0		17.2			
13.5		16.0			
14.0		15.3	17.0		
14.5					
15.0			14.3	13.1	12.0
15.5			14.3	12.8	
16.0				12.7	11.8
16.5				12.7	11.8
17.0					11.8
17.5					
18.0					
Total					
Depth, m	8.5	14.6	16	16.8	17.5
Start time	15:21	15:09	15:03	14:46	14:35

8 August 2007 mg/L (1st trial)

Depth, m	BR0.5	BR1	BR1.5	BR2	BR3	BR4	BR5
0.0							
0.5	9.1	7.4	8.3	8.1	8.0	8.3	8.0
1.0							
1.5							
2.0							
2.5							
3.0	2.7	2.4	6.4	8.3	8.3	5.4	8.7
3.5							
4.0							
4.5							
5.0	2.2						
5.5							
6.0	1.6	1.7	2.6	3.3	3.4	2.5	2.3
6.5	1.4						
7.0							
7.5							
8.0							
8.5							
9.0		1.3					
9.5							
10.0		1.3					
10.5		1.2					
11.0		1.1					
11.5			1.9				
12.0			1.6	2.3	1.7	1.4	1.7
12.5			1.4				
13.0				2.0			
13.5				1.7		1.3	
14.0				1.6	1.6	1.4	
14.5						1.4	
15.0					1.5	1.3	1.5
15.5					1.4		1.5
16.0							1.5
16.5							
17.0							
17.5							
18.0							
Total Depth, m	7.1	11.5	13.2	14.6	15.8	15.5	16.7
Start time	8:30	8:40	8:50	9:00	9:10	9:22	9:38

8 August 2007 Temperature

Depth, m	BR0.5	BR1	BR1.5	BR2	BR3	BR4	BR5
0.0							
0.5	24.5	24.4	24.2	24.1	24.0	24.0	24.0
1.0							
1.5							
2.0							
2.5							
3.0	24.5	24.3	24.1	24.1	24.0	24.0	24.0
3.5							
4.0							
4.5							
5.0	24.5						
5.5							
6.0	24.5	24.3	24.1	24.1	24.0	23.9	23.9
6.5	24.5						
7.0							
7.5							
8.0							
8.5							
9.0		24.3					
9.5							
10.0		22.2					
10.5		19.1					
11.0		18.2					
11.5			18.8				
12.0			17.5	20.3	23.5	23.9	23.8
12.5			17.3				
13.0				17.4			
13.5				17.1		23.3	
14.0				17.1	17.7	19.7	
14.5						17.7	
15.0					17.6	17.4	18.9
15.5					17.6		17.0
16.0							16.0
16.5							
17.0							
17.5							
18.0							
Total Depth, m	7.1	11.5	13.2	14.6	15.8	15.5	16.7
Start time	8:30	8:40	8:50	9:00	9:10	9:22	9:38

8 August 2007 mg/L

Depth, m	AP1	AP1.5	AP2	AP3	AP4
0.0					
0.5	7.5	7.7	7.9	7.9	7.6
1.0					
1.5					
2.0					
2.5					
3.0	7.1	7.7	8.3	8.7	4.0
3.5					
4.0					
4.5					
5.0					
5.5					
6.0	3.4	2.7	3.1	1.9	2.7
6.5					
7.0	2.3				
7.5	2.0				
8.0	1.8				
8.5					
9.0					
9.5					
10.0					
10.5					
11.0					
11.5					
12.0		1.7	1.8	1.5	1.7
12.5					
13.0		1.5			
13.5		1.3			
14.0		1.1			
14.5			1.6		
15.0			1.5	1.6	1.6
15.5			1.4		
16.0				1.6	1.6
16.5				1.6	1.7
17.0					1.8
17.5					
18.0					
Total Depth, m	8.7	14.7	16.2	16.8	17.5
Start time	11:09	10:57	10:46	10:31	10:07

8 August 2007 Temperature

Depth, m	AP1	AP1.5	AP2	AP3	AP4
0.0					
0.5	25.2	24.5	24.4	24.3	24.2
1.0					
1.5					
2.0					
2.5					
3.0	25.0	24.4	24.3	24.2	24.1
3.5					
4.0					
4.5					
5.0					
5.5					
6.0	24.8	24.3	24.2	24.1	24.0
6.5					
7.0	24.6				
7.5	24.4				
8.0	24.3				
8.5					
9.0					
9.5					
10.0					
10.5					
11.0					
11.5					
12.0		23.8	23.4	23.6	23.7
12.5					
13.0		16.2			
13.5		15.1			
14.0		14.7			
14.5			14.6		
15.0			13.3	14.8	17.3
15.5			13.3		
16.0				12.4	15.0
16.5				12.3	13.6
17.0					12.0
17.5					
18.0					
Total Depth, m	8.7	14.7	16.2	16.8	17.5
Start time	11:09	10:57	10:46	10:31	10:07

s

8 August 2007			**mg/L**		(2nd trial)		
Depth, m	BR0.5	BR1	BR1.5	BR2	BR3	BR4	BR5
0.0							
0.5	7.2	7.5	7.7	7.6	7.9	7.5	9.3
1.0							
1.5							
2.0							
2.5							
3.0	6.8	7.3	7.3	7.5	7.8	7.7	9.1
3.5							
4.0							
4.5							
5.0							
5.5	6.6						
6.0	6.5	7.7	5.3	5.8	2.8	2.6	1.7
6.5	6.4						
7.0	6.3						
7.5							
8.0							
8.5							
9.0		2.3	2.0	2.5		1.6	
9.5							
10.0		2.0					
10.5		1.6					
11.0		1.3					
11.5			1.8				
12.0			1.6	2.0	1.8	1.3	1.4
12.5			1.5				
13.0				1.8			
13.5				1.6			
14.0				1.5	1.7	1.4	
14.5					1.5	1.3	
15.0					1.4	1.3	1.5
15.5					1.4		1.5
16.0							1.4
16.5							
17.0							
17.5							
18.0							
Total							
Depth, m	7.5	11.5	13.1	14.6	15.8	15.5	16.5
Start time	13:11	13:01	12:50	12:39	12:28	12:13	12:00

8 August 2007			**Temperature**				
Depth, m	BR0.5	BR1	BR1.5	BR2	BR3	BR4	BR5
0.0							
0.5	25.1	25.1	24.9	24.7	24.4	24.5	24.5
1.0							
1.5							
2.0							
2.5							
3.0	24.6	24.5	24.3	24.3	24.1	24.1	24.1
3.5							
4.0							
4.5							
5.0							
5.5	24.6						
6.0	24.6	24.4	24.2	24.1	24.0	24.0	23.9
6.5	24.6						
7.0	24.5						
7.5							
8.0							
8.5							
9.0		24.1	24.2	24.1		23.9	
9.5							
10.0		22.3					
10.5		19.2					
11.0		18.3					
11.5			19.5				
12.0			18.2	20.6	23.8	23.7	23.6
12.5			17.4				
13.0				17.4			
13.5				17.1			
14.0				17.1	17.7	18.1	
14.5					17.5	17.4	
15.0					17.5	17.2	17.6
15.5					17.5		16.3
16.0							15.5
16.5							
17.0							
17.5							
18.0							
Total							
Depth, m	7.5	11.5	13.1	14.6	15.8	15.5	16.5
Start time	13:11	13:01	12:50	12:39	12:28	12:13	12:00

9 August 2007 mg/L

Depth, m	AP1	AP1.5	AP2	AP3	AP4
0.0					
0.5				9.5	11.4
1.0					
1.5					
2.0					
2.5					
3.0				15.3	10.2
3.5					
4.0					
4.5					
5.0					
5.5					
6.0				13.5	5.4
6.5					
7.0					
7.5					
8.0					
8.5					
9.0				5.2	3.8
9.5					
10.0					
10.5					
11.0					
11.5					
12.0					3.4
12.5					
13.0					
13.5					
14.0					
14.5					
15.0				5.1	3.5
15.5					
16.0				4.3	3.4
16.5				3.7	3.3
17.0					3.4
17.5					
18.0					
Total					
Depth, m				17	17.5
Start time				9:20	9:05

9 August 2007 Temperature

Depth, m	AP1	AP1.5	AP2	AP3	AP4
0.0					
0.5				24.4	24.5
1.0					
1.5					
2.0					
2.5					
3.0				24.5	24.5
3.5					
4.0					
4.5					
5.0					
5.5					
6.0				24.5	24.4
6.5					
7.0					
7.5					
8.0					
8.5					
9.0				23.9	24.0
9.5					
10.0					
10.5					
11.0					
11.5					
12.0					23.0
12.5					
13.0					
13.5					
14.0					
14.5					
15.0				13.8	17.0
15.5					
16.0				12.4	12.6
16.5				12.4	12.1
17.0					12.0
17.5					
18.0					
Total					
Depth, m				17	17.5
Start time				9:20	9:05

9 August 2007 mg/L

Depth, m	BR0.5	BR1	BR1.5	BR2	BR3	BR4	BR5
0.0							
0.5	8.6						
1.0							
1.5							
2.0							
2.5							
3.0	15.8						
3.5							
4.0							
4.5							
5.0	8.4						
5.5	4.8						
6.0	4.2						
6.5	4.0						
7.0							
7.5							
8.0							
8.5							
9.0							
9.5							
10.0							
10.5							
11.0							
11.5							
12.0							
12.5							
13.0							
13.5							
14.0							
14.5							
15.0							
15.5							
16.0							
16.5							
17.0							
17.5							
18.0							
Total							
Depth, m	7.1						
Start time	9:56						

9 August 2007 Temperature

Depth, m	BR0.5	BR1	BR1.5	BR2	BR3	BR4	BR5
0.0							
0.5	24.7						
1.0							
1.5							
2.0							
2.5							
3.0	24.6						
3.5							
4.0							
4.5							
5.0	24.4						
5.5	24.4						
6.0	24.4						
6.5	24.4						
7.0							
7.5							
8.0							
8.5							
9.0							
9.5							
10.0							
10.5							
11.0							
11.5							
12.0							
12.5							
13.0							
13.5							
14.0							
14.5							
15.0							
15.5							
16.0							
16.5							
17.0							
17.5							
18.0							
Total							
Depth, m	7.1						
Start time	9:56						

10 August 2007 mg/L (1st trial)

Depth, m	AP1	AP1.5	AP2	AP3	AP4
0.0					
0.5	8.7	9.6	9.3	9.5	12.3
1.0					
1.5					
2.0					
2.5					
3.0	8.9	9.3	9.2	9.6	11.5
3.5					
4.0					
4.5					
5.0					
5.5					
6.0	9.1	9.7	10.7	8.2	7.4
6.5					
7.0	8.8				
7.5	9.1				
8.0	8.9				
8.5					
9.0		10.6	11.2	6.6	5.7
9.5					
10.0					
10.5					
11.0					
11.5					
12.0		8.4	6.5	5.0	5.0
12.5					
13.0		6.7			
13.5		4.8			
14.0		4.3			
14.5			3.4		
15.0			2.6	3.5	3.7
15.5			2.0	3.0	
16.0				2.9	3.4
16.5				2.8	3.2
17.0					3.1
17.5					
18.0					
Total					
Depth, m	8.6	14.7	16.3	17	17.5
Start time	10:03	9:55	9:42	9:22	9:00

10 August 2007 Temperature

Depth, m	AP1	AP1.5	AP2	AP3	AP4
0.0					
0.5	24.8	24.4	24.4	24.3	24.2
1.0					
1.5					
2.0					
2.5					
3.0	24.8	24.4	24.5	24.3	24.2
3.5					
4.0					
4.5					
5.0					
5.5					
6.0	24.5	24.4	24.5	24.3	24.2
6.5					
7.0	24.4				
7.5	24.4				
8.0	24.4				
8.5					
9.0		24.3	24.4	24.0	24.2
9.5					
10.0					
10.5					
11.0					
11.5					
12.0		22.8	21.9	22.0	22.5
12.5					
13.0		20.5			
13.5		20.1			
14.0		19.2			
14.5			15.8		
15.0			15.7	16.4	18.0
15.5			15.6	14.8	
16.0				13.4	14.3
16.5				12.6	12.5
17.0					12.5
17.5					
18.0					
Total					
Depth, m	8.6	14.7	16.3	17	17.5
Start time	10:03	9:55	9:42	9:22	9:00

10 August 2007 mg/L

Depth, m	BR0.5	BR1	BR1.5	BR2	BR3	BR4	BR5
0.0							
0.5	9.0	9.6	9.3	9.4	9.7	9.5	9.4
1.0							
1.5							
2.0							
2.5							
3.0	8.8	9.4	9.2	9.4	9.6	9.7	9.5
3.5							
4.0							
4.5							
5.0							
5.5							
6.0	10.7	10.6	7.9	9.8	11.4	10.2	10.3
6.5	10.2						
7.0	9.7						
7.5							
8.0							
8.5							
9.0		3.6	3.5	10.6	3.7	10.6	10.7
9.5							
10.0		2.9					
10.5		2.6					
11.0		2.5					
11.5			2.7				
12.0			2.6	10.6	2.6	10.8	10.7
12.5			2.6				
13.0				9.0			
13.5				5.5			
14.0				5.1	2.4	10.6	
14.5					2.2	6.2	
15.0					2.1	4.6	8.4
15.5							2.7
16.0							2.4
16.5							
17.0							
17.5							
18.0							
Total							
Depth, m	7.5	11.7	13.4	14.6	15.9	15.5	16.7
Start time	10:10	10:47	10:55	11:07	11:22	11:37	11:52

10 August 2007 Temperature

Depth, m	BR0.5	BR1	BR1.5	BR2	BR3	BR4	BR5
0.0							
0.5	24.6	24.6	24.6	24.5	24.3	24.2	24.3
1.0							
1.5							
2.0							
2.5							
3.0	24.6	24.7	24.6	24.5	24.3	24.2	24.2
3.5							
4.0							
4.5							
5.0							
5.5							
6.0	24.6	24.7	24.6	24.4	24.3	24.2	24.2
6.5	24.6						
7.0	24.6						
7.5							
8.0							
8.5							
9.0		24.7	24.5	24.4	24.3	24.2	24.1
9.5							
10.0		24.7					
10.5		24.6					
11.0		24.5					
11.5			23.4				
12.0			23.0	22.9	23.6	24.1	24.1
12.5			22.2				
13.0				20.3			
13.5				19.1			
14.0				19.0	19.3	21.5	
14.5					18.1	19.0	
15.0					17.9	18.2	18.4
15.5							15.8
16.0							15.6
16.5							
17.0							
17.5							
18.0							
Total							
Depth, m	7.5	11.7	13.4	14.6	15.9	15.5	16.7
Start time	10:10	10:47	10:55	11:07	11:22	11:37	11:52

10 August 2007	mg/L				
Depth, m	AP1	AP1.5	AP2	AP3	AP4 (2nd trial)
0.0					
0.5	9.0	9.5	9.2	9.3	9.7
1.0					
1.5					
2.0					
2.5					
3.0	9.3	9.6	9.4	9.9	9.9
3.5					
4.0					
4.5					
5.0					
5.5					
6.0	9.6	10.4	10.4	10.7	10.8
6.5					
7.0	9.3				
7.5	9.2				
8.0	9.2				
8.5					
9.0		10.5	10.6	11.1	10.7
9.5					
10.0					
10.5					
11.0					
11.5					
12.0		6.6	6.9	10.6	11.3
12.5					
13.0		5.9			
13.5		3.5			
14.0		2.5			
14.5			2.9		
15.0			2.1		6.4
15.5			1.7	4.8	
16.0				4.2	4.6
16.5				3.5	3.6
17.0					3.6
17.5					
18.0					
Total					
Depth, m	8.6	14.5	16.2	17	17.5
Start time	13:20	13:09	12:56	12:43	12:28

10 August 2007	Temperature				
Depth, m	AP1	AP1.5	AP2	AP3	AP4
0.0					
0.5	24.9	24.7	24.7	24.5	24.4
1.0					
1.5					
2.0					
2.5					
3.0	24.8	24.7	24.6	24.5	24.4
3.5					
4.0					
4.5					
5.0					
5.5					
6.0	24.6	24.6	24.5	24.4	24.3
6.5					
7.0	24.6				
7.5	24.6				
8.0	24.6				
8.5					
9.0		24.5	24.4	24.0	24.3
9.5					
10.0					
10.5					
11.0					
11.5					
12.0		22.2	21.4	22.9	23.4
12.5					
13.0		21.2			
13.5		19.0			
14.0		17.6			
14.5			16.4		
15.0			16.1		17.5
15.5			15.5	14.4	
16.0				14.1	15.6
16.5				12.8	13.3
17.0					13.1
17.5					
18.0					
Total					
Depth, m	8.6	14.5	16.2	17	17.5
Start time	13:20	13:09	12:56	12:43	12:28